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ORIGIN OF ROCK CREEK AND OWENS RIVER GORGES MONO COUNTY, CALIFORNIA

BY

WILLIAM C. PUTNAM

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
1960

UNIVERSITY OF CALIFORNIA PUBLICATIONS IN GEOLOGICAL SCIENCES

EDITORS (LOS ANGELES): W. C. PUTNAM, DONALD CARLISLE, E. L. WINTERER

Volume 34, No. 5, pp. 221–280, plates 31–40, 1 figure and 1 map in pocket,
2 figures and 2 maps in text

Submitted by editors November 5, 1958
Issued March 7, 1960
Price, $2.00

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
CALIFORNIA

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CAMBRIDGE UNIVERSITY PRESS
LONDON, ENGLAND

PRINTED IN THE UNITED STATES OF AMERICA

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ORIGIN OF ROCK CREEK AND OWENS RIVER GORGES, MONO COUNTY, CALIFORNIA

BY

WILLIAM C. PUTNAM

ABSTRACT

Owens River and Rock Creek now follow subparallel courses in deep gorges cut across a plateau of Late Pleistocene rhyolitic pumice and tuff immediately east of the central Sierra Nevada in California.

The accumulation of tills of three glacial stages, which in order of decreasing age are the Sherwin, Tahoe, and Tioga, in addition to more than 500 feet of pumice and tuff, blocked the drainage of most of the streams in this region on the eastern slope of the Sierra Nevada. Faulting has also been active here throughout the Quaternary, and, together with warping, was responsible for the uplift of the Sierra Nevada, as well as the depression of the neighboring basin of Long Valley.

This valley was occupied by a large lake, presumably during the latter part of the Pleistocene, which was drained through capture resulting from the headward growth of the Owens River across the blanket of rhyolitic tuff covering the volcanic tableland. The Owens Gorge very likely was excavated to its present-day depth as a consequence of the greatly increased flow of the Owens River resulting from this capture.

Rock Creek, which had formerly drained northward to Long Valley, was captured at a somewhat later date, and also by headward growth of a stream following a course roughly parallel to the Owens River, with the result that its gorge was eroded to its depth of today, partly as a consequence of greatly enhanced discharge.

INTRODUCTION

General Statement

Rock Creek and the Owens River flow southeastward in two nearly parallel canyons cut across a broad plateau of rhyolite tuff at the east base of the Sierra Nevada immediately northwest of Bishop, California. Owens Gorge, with a maximum depth of approximately 800 feet, is larger and physiographically older than Rock Creek Gorge. The course of the Owens Gorge apparently was established by headward growth and capture following eruption of the Bishop tuff in the latter part of the Pleistocene Epoch. Rock Creek established its course by essentially the same means somewhat later, about the third glacial stage (Tahoe) in the eastern Sierra Nevada. The purpose of this paper is to demonstrate how closely the origin of these canyons is related to the nature and structure of the bedrock, and how the evolution of the landforms of the area has been controlled by the volcanic, glacial, lacustrine, and tectonic history of the region during the Pleistocene and Recent epochs.

Previous Work

Little attention was paid to the geology of this sector of the eastern Sierra Nevada before 1900 in spite of the considerable mining activity in immediately adjacent districts, especially in the Benton Range, where mining started in the 1870's just north of the area mapped (Rinehart and Ross, 1956).

The first significant geologic reconnaissance of this area was made by W. T.

Lee (1906), who reported upon the feasibility of the Owens Gorge as a possible dam site for an irrigation project to serve the ranches of the Owens Valley. In the opinion of those soon-to-be evicted owners, this was only a smoke screen thrown up by the city of Los Angeles in order to gain a paramount water right through the creation of a fictitious reclamation district (Chalfant, 1933; Mayo, 1933).

Not until the 1930's did interest in the structural and geomorphic history of the area really begin. This is a critical location in Blackwelder's (1931) glacial sequence for the eastern Sierra Nevada, because the type locality of his Sherwin glacial stage is in part of the area immediately adjacent to Rock Creek Gorge. This same area was also described by Kesseli (1941) as part of a general study of the glaciation of the east-central Sierra Nevada.

E. B. Mayo, while a student of Blackwelder's, made a reconnaissance geologic map of the eastern Sierra Nevada from Rock Creek to June Lake for his doctoral thesis at Stanford University, and also published a paper concerned with the structural evolution of this part of the Sierra Nevada (1941), as well as a brief note on the origin of Long Valley trough and the history of the lake that once occupied it (1934).

Two papers of fundamental importance are those by Gilbert: the first (1938) is concerned with the origin of the Bishop tuff, whose type locality is part of the area mapped, and the second (1941) discusses the structural evolution of the east-central Sierra Nevada in regional terms.

The area immediately adjacent to the south, in the vicinity of Bishop, has been mapped in detail by Bateman (1950, 1956, 1958), and his studies have been of great help to me since many of his rock units and structures extend northward into this area.

The geology of the Casa Diablo Mountain Quadrangle, approximately the southern one-third of which constitutes the area described in this paper, has been mapped recently by Rinehart and Ross (1956, 1957). Although the areas of our investigations overlap, the emphasis of each paper is quite different. Their study is concerned chiefly with the economic geology of the tungsten deposits of the Benton Range, and with the origin of the igneous and metamorphic rocks of the area, whereas the emphasis of this study is primarily on the glacial history and the evolution of the drainage pattern. The two geologic maps were prepared quite independently and show the usual degree of dissimilarity to be expected from the work of individual investigators. The chief differences are in the fault pattern, and this is largely a matter of interpretation rather than observation, because of the widespread blanket of surficial deposits in this area.

A gravimetric survey of the Long Valley trough was completed recently by the Geophysical Branch of the U.S. Geological Survey, and the preliminary results were reported in an abstract by Pakiser and Kane (1956).

As part of a larger inquiry into the late-glacial history of the central Sierra Nevada, Birman (1957) extended his mapping of moraines and related features down the canyon of Rock Creek into the western part of the area. He succeeded in establishing several subdivisions of Blackwelder's original four glacial stages, especially in the Tahoe, which he has separated into two units.

NATURE OF THE INVESTIGATION

Field work on this project was started in 1948, and was carried on in spite of numerous interruptions during the following summers until 1954.

Mapping was done on aerial photographs, of an approximate scale of 1:24,000, which were taken in 1944 by Fairchild Aerial Surveys, Inc., for the Department of Water and Power of the city of Los Angeles. Observations were plotted on these in the field by means of a 2x lens-type pocket stereoscope and then transferred to an enlarged (1:48,000) copy of the U.S. Geological Survey's Casa Diablo Mountain Quadrangle (1:62,500).

In addition to acquiring information by conventional field methods, I was indeed fortunate in being able to make detailed observations along the entire length of Tunnel No. 1 of the Owens Gorge Project of the Department of Water and Power, and to inspect the cores and logs of test holes drilled at various places along the tunnel alignment. This information was of the greatest assistance to me in estimating the thicknesses of glacial and volcanic formations and the displacement of faults crossing the tunnel line.

ACKNOWLEDGMENTS

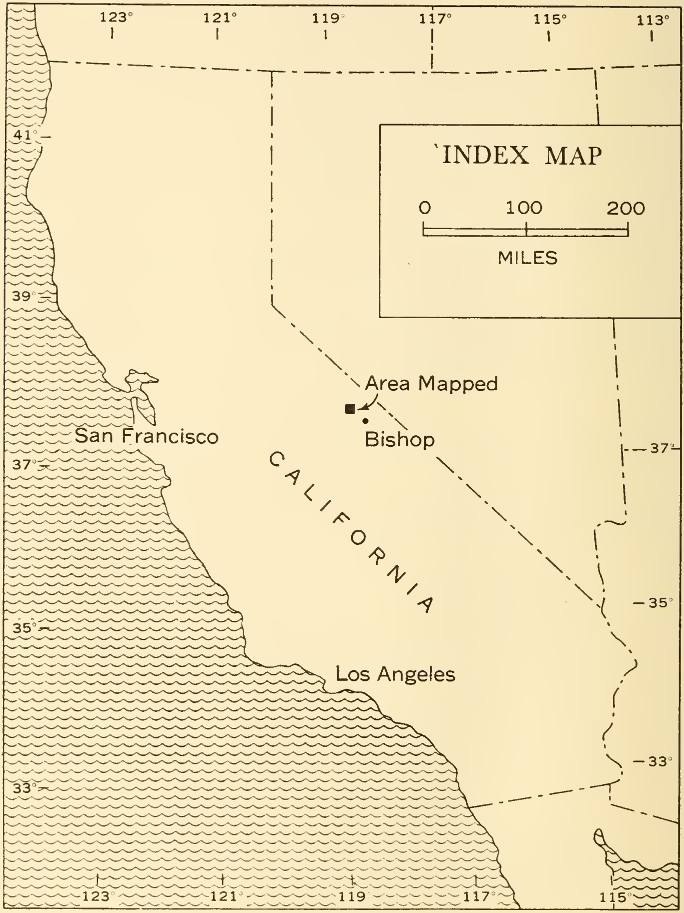
The suitability of this area for study of the later geologic history of the Sierra Nevada was first suggested to me by Paul C. Bateman of the U.S. Geological Survey, and I am indeed grateful to him for advice and assistance throughout the course of the project. Dean Rinehart and Donald C. Ross, both of the Geological Survey, were of great help in the field and in discussions, as part of the time their field work coincided with mine. Talks with Joseph Birman of the Department of Geology, Occidental College, were especially useful in arriving at an understanding of the glacial stratigraphy of this area as it relates to the western slope and interior parts of the Sierra Nevada. I am indeed happy to acknowledge my indebtedness to my colleague D. I. Axelrod for many long and fruitful debates on problems of the Sierra Nevada and for his searching review of this paper, and I wish to express my obligation to Mrs. Peter Kurtz for her skill and care in drafting the accompanying maps and sections.

I am deeply indebted to officials of the Los Angeles Department of Water and Power for having granted me access to Owens Gorge Tunnel No. 1, and for having extended every possible courtesy to me. Among those who were especially helpful were Samuel B. Morris, then general manager and chief engineer; William Mason, project engineer; O. M. Lloyd, deputy city attorney; Leon Turner, department engineer; and Lewis M. Sanborn, tunnel inspector. Mr. Sanborn was responsible for preparing a detailed record and geologic cross section along the tunnel line, and his observations were both accurate and extremely helpful.

GEOGRAPHY

REGIONAL SETTING

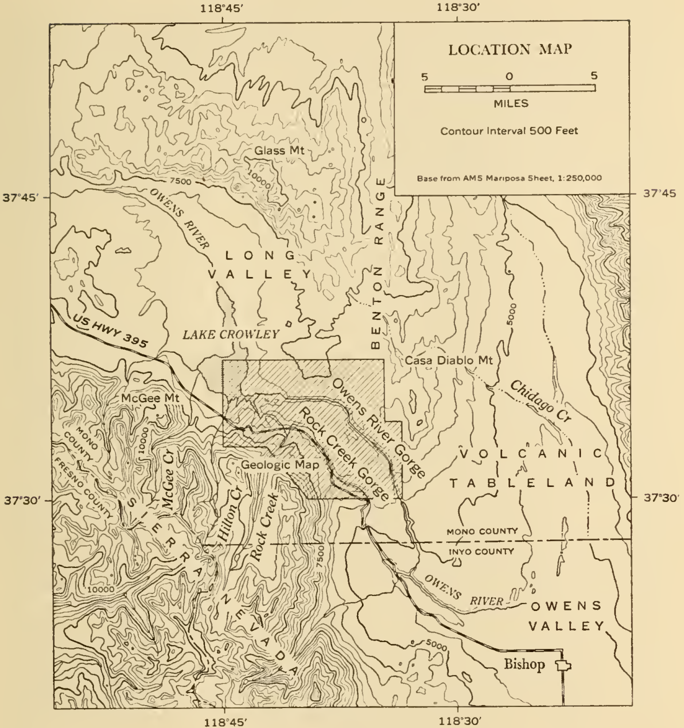
The index map (map 2) shows that the area is about 300 miles north of Los Angeles, from which city it can be reached by U.S. Highway 395. It is on the eastern slope of the Sierra Nevada, and hydrologically is part of the Great Basin



Map 2. Index map.

because all streams are tributary to the Owens River which terminates in Owens Lake, a saline playa.

The principal terrain element of the area is a broad platform of rhyolitic tuff which is trenched by the gorges of Owens River and Rock Creek. This plateau, the Volcanic Tableland, is bounded on the west by the bold escarpment of the



Map 3. Location map.

Sierra Nevada, whose summit rises 4,300 feet above the tableland. The tableland itself forms a barrier between the two structural troughs, Long Valley to the north and Owens Valley to the south. Long Valley, an enclosed basin occupied by a lake during the Pleistocene, has an average altitude of 6,800 feet, while the adjacent Owens Valley at Bishop is 4,100 feet above sea level. It is this difference in altitude that is responsible for the steep gradients of the Owens River and Rock Creek.

The area comprises three topographic provinces: (1) the Sierra Nevada, (2) the Volcanic Tableland, and (3) the southern part of Long Valley.

SIERRA NEVADA

This lofty mountain range dominates the western part of the area. There are no foothills, and the range is bordered by an escarpment 4,300 feet high with an average slope of about 25°. Perhaps the most precipitous part of the mountain front is the east side of Wheeler Crest, a spectacular ridge of light-gray granite which rises nearly 6,000 feet in 2 miles. This ridge is a short distance south of Rock Creek in the Mount Tom Quadrangle, immediately south of the area mapped.

The most striking feature of the range front in plan, and a matter of great significance structurally, is the abrupt change in trend from approximately north-south along the Wheeler Crest to nearly east-west where Rock Creek Canyon leaves the Sierra Nevada. Such abrupt changes in direction are characteristic of this part of the Sierra Nevada, which here consists of a succession of bold salients and deep reëntrants in contrast to the simple linear pattern of the mountain front bordering Owens Valley south of Bishop. This right-angle change in direction is also reflected by Rock Creek and Owens gorges which alter their courses from east to nearly due south opposite the mouth of Rock Creek Canyon.

The Sierran escarpment in this area is uninterrupted by major canyons, except for those of Rock and Hilton creeks. All others are little more than ravines scored into the mountain front. The valleys of these two major streams have been glaciated, and both have extensive deposits of glacial till bordering them. Rock Creek, especially, has been strongly modified by glaciation, and in the Sierran segment of its course runs in a canyon 800 feet deep which is flanked by prominent lateral moraines, except at the very mouth, where the stream flows in a granite defile.

The geologic map (map 1, in pocket) demonstrates that the range is not bordered by a single marginal fault, but is blocked out by many roughly parallel fractures whose individual displacements may be small, but whose cumulative offsets are large. The range, in part, has been stepped up in a succession of slices, which are reflected in the landscape by a number of benches that, seen from a distance in profile, resemble the treads and risers of a cyclopean stairway. This bench and slope pattern is most pronounced west of Rock Creek Canyon where one prominent bench is at 8,500 feet; 3,000 feet below the summit of the range and 1,500 feet above the Volcanic Tableland.

The fact that many of the marginal faults have dips in excess of 70°, while the maximum slope of the Sierran front rarely exceeds 30°, shows that the range front is not the original fault scarp, but is an eroded surface whose inclination represents a temporary slope stability for the dominant rock types and kind of weathering operating here. Gilluly (1928) described a similar relationship for the Oquirrh Range in Utah, noting that the slope of a mountain front is a function of rock resistance to degradation, rather than a direct reflection of the attitude of the frontal fault plane. This appears to have been substantially the view of Bryan (1940); an equilibrium slope will be developed for a given rock type, vegetative cover, and dominant kind of weathering.

The absence of large alluvial fans is a conspicuous feature of this part of the Sierra Nevada, where the base of the range is at an altitude of over 7,000 feet, in contrast to farther south where the base is at an altitude of 4,000 feet. This absence of fans may be owing to the lack of large streams here as well as the drier climate to the south, but it also appears in some measure to be the result of mass transport and erosion at high altitudes. Most of the precipitation is in winter, and much of it falls as snow. Frost shattering is a powerful force here, and many slopes are mantled by long streams of ice-riven joint blocks. The bedrock surface near the base of the escarpment is effectively armored against the gradual release of water from snow melting by a protective blanket of block streams and talus. The only large alluvial fans are at the mouths of Hilton and Rock Creek canyons, both of which hold perennial streams draining large areas of till; thus, both have an abundant supply of water and detrital material with which to work.

An impressive result of frost action on the relatively closely jointed rocks of this part of the Sierra Nevada is the development of upland surfaces paved with sharp-edged rock fragments. These testify to the efficacy of frost-riving and lend support to Daly's (1905) early contention that accordant summits of alpine mountains may result more often from the leveling effect of erosional processes at high altitudes than from the preservation of peneplain remnants.

VOLCANIC TABLELAND

This broad, tuff-covered plateau is essentially a down-dropped block between the Sierra Nevada on the south and the Benton Range and Glass Mountain on the north and east. The geologic map (map 1) shows that most of the tableland north and south of the Owens Gorge is covered by rhyolite tuff with a few buried granite hills projecting through it locally.

The tuff of the Volcanic Tableland appears to have been flexed into a broad arch whose flanks slope gently toward Long Valley to the northwest and Owens Valley to the southeast. The axis of this arch trends about N. 10° W. between Sherwin Hill near the edge of the mapped area and the granitic center of Round Mountain near the north edge. This trend roughly parallels the line of granitic knobs that project through the tuff and the buried granitic ridge that was found in Tunnel No. 1.

Probably the most striking feature of this terrain unit is the gorges of Rock Creek and the Owens River. Owens Gorge is the larger of the two and has a maximum depth of 900 feet, while the greatest depth of Rock Creek Gorge is approximately 600 feet. Both gorges have flaring cross-profiles with only a slight tendency towards a step-and-bench profile, even though they are cut in nearly flat-lying layers of pumice and tuff for most of their length. Owens Gorge cuts completely through the volcanic rocks near its midpoint, and there exposes a buried ridge of granitic rocks nearly 700 feet high which is flanked by basalt flows and breccias. Rock Creek Gorge is cut chiefly in Sherwin till, but immediately north of Sherwin Hill the entire gorge is incised in a recently unroofed ridge of granitic rocks and hornfels capped by a thin veneer of glacial debris and Bishop tuff.

In a general way, the tableland has a uniformly sloping surface, but in detail much of it is very rough. Craggy ridges are separated from one another by pumice-floored swales, many of which are undrained. The ridges, some of which are 30 to 50 feet high, may have nearly vertical walls and consist of mural-jointed red or pink tuff. Higher parts of the plateau support an open, parklike forest of Jeffery pine with an undergrowth of sage. This is a confusing region in which to do field work since the landscape appears much the same over a great deal of it and there are no through-flowing streams to serve as guides. On aerial photographs the country has a grained appearance, resembling bark, and this is undoubtedly an expression of the closely spaced fracture pattern in the brittle tuff.

LONG VALLEY

Only the southern end of this 12-mile-long fault trough is in the area. Long Valley is bounded by the Sierra Nevada to the west, the steep front of Glass Mountain to the east, and the Volcanic Tableland to the south. The northern part of the valley is interrupted by a group of low volcanic hills. The western side has long lateral moraines extending well out into the valley at the mouths of Hilton and McGee creeks, with the most prominent set at McGee Creek.

That Long Valley was occupied by a large Pleistocene lake is readily apparent (Mayo, 1934), and at its southern end the lake was about 300 feet deep. A well-defined upper shore line at an altitude of approximately 7,000 feet is cut in the Bishop tuff east of Owens Gorge at Long Valley Dam, which marks the extreme south end of the old lake. The shore line is less distinct on the west side of Long Valley, possibly because this was the windward side of the lake as well as being the shore that was sheltered in the lee of the Sierra Nevada. Lake gravels cover the wave-cut surface of rhyolite tuff east of the Owens River and have a maximum thickness of 50 to 75 feet. Lake terraces are less prominent west of the river, especially on the higher lake levels. The sublacustrine topography reflects this difference as well. The tuff east of the river has been planed off into nearly level treads which are blanketed by a thick layer of gravel. West of the river and at the south end of Long Valley the rhyolite tuff makes craggy pinnacles and isolated ridges. In fact, it is in this scoured area, higher than the lake beds shown on the geologic map and below the 7,000-foot contour, that the close spacing of the fractures cutting the tuff is most apparent on aerial photographs. The reason for this strong difference in appearance is not immediately obvious, however. It may be partly the result of the pattern of currents within the lake; in general, the eastern side seems to have been primarily a site of deposition, the western of scour.

The floor of Long Valley, within the area mapped, is now concealed by Lake Crowley, an artificial waterbody created through the blocking of the Owens River by the Long Valley Dam. Before it was flooded, the visible valley floor consisted of the floodplain deposits of the Owens River and its tributaries, such as McGee and Hilton creeks. Lake clay, marl, limy layers, and silica-cemented sandstone are more typical of the floor of Long Valley north of Lake Crowley.

The western side of the valley is bordered by fluvial and glacial detritus supplied by streams and glaciers from the Sierra Nevada. The eastern shore of Lake Crowley, for much of the distance included within the area mapped, is an impressive lake-cliff cut in the widely spread, west-sloping blanket of white pumice underlying the rhyolite tuff of the Volcanic Tableland.

CLIMATE AND VEGETATION

The climate is strongly influenced by the position of the area to leeward of a high range marginal to a desert. The mapped area lies almost wholly within the steppe, but as a consequence of its generally high altitude, which averages 7,000 feet, it has many of the attributes of a mountain climate as well.

The accompanying climatic data (table 1) for Long Valley Dam and Bishop show that the precipitation is almost entirely confined to the winter, and most of it falls as snow. Summer thundershowers occur but are in the uplands chiefly. In the vicinity of the Long Valley Dam these rarely do more than wet the ground; it is indeed uncommon for significant runoff to result. This may be the consequence, in part, of the high permeability of the rhyolite tuff and glacial till that blanket most of the area.

The area straddles the boundary between the Sonoran and Transition Life Zones, which here is close to the 6,800-foot contour. Below this level the vegetation is almost wholly Basin sage, rabbit brush, bitter brush, and bunch grass. A scattered piñon-juniper woodland characterizes the Volcanic Tableland at altitudes between 6,500 and 7,000 feet. Above 7,000 feet open stands of Jeffery pine give a parklike appearance to the rhyolite plateau. In addition to altitude, there are other factors controlling the distribution of vegetation. Chief among these seem to be the kind of ground and the available soil moisture. For example, Jeffery pine flourishes on the rhyolite tuff, but shuns glacial till. Junipers do not grow on the tuff in significant numbers above 7,000 feet where the Jeffery pine commences to flourish, but dominate over pine on granitic rocks up to nearly 8,600 feet, the highest altitude mapped.

TABLE 1

CLIMATIC DATA[a]

	Bishop (approx. 4,100 feet)		Long Valley Dam (approx. 7,000 feet)	
	Average temp. (° F.)	Precipitation (in inches)	Average temp.[b] (° F.)	Precipitation (in inches)
January	37	1.77	....	1.43
February	42	0.94	....	1.74
March	46	0.87	....	1.11
April	53	0.22	....	0.56
May	59	0.28	....	0.44
June	67	0.11	....	0.33
July	73	0.11	....	0.30
August	71	0.14	....	0.28
September	64	0.22	....	0.20
October	55	0.20	....	0.45
November	46	0.30	....	0.89
December	38	0.89	....	1.81
Annual	54	6.05	....	9.54

[a] Climatic data supplied by the Los Angeles Office, U.S. Weather Bureau.

[b] No temperature figures were available for Long Valley Dam, but the Bureau estimates that temperatures there would average 10° less than at Bishop.

Notable zone crossers are willow and aspen, which line the banks of Rock Creek and the Owens River, as well as the smaller perennial streams. This occurrence is also typical of the Jeffery pine. Isolated individuals and small groves grow along the banks of the Owens River and Rock Creek, deep within their respective gorges, down to an altitude of 6,000 feet, which is 1,000 feet lower than their minimum range on the tableland.

Sage and other associated shrubs also range across the entire area, and on this dry, leeward slope of the Sierra grow up into the Alpine Zone at an altitude of 11,000 feet.

Meadows, such as Little Round Valley, Witcher Meadow, and those bordering Lake Crowley, are grass-carpeted and also support dense thickets of willow. They are used during the summer for grazing sheep and cattle, as are the bleak expanses of sage and rabbit brush east of Lake Crowley.

ROCK UNITS

Paleozoic and Precambrian Contact-Metamorphic Rocks

The oldest rocks of the area are several small, isolated bodies exposed on the walls and adjacent shoulders of Rock Creek Gorge a short distance northwest of Sherwin Hill. The width of each outcrop is less than 0.2 mile, and only the southernmost of the three is exposed for nearly the full height of the canyon walls, here approximately 500 feet high.

These rocks appear to have been originally shale, sandstone, limy beds, and limestone which are now metamorphosed to quartz-sericite hornfels, calc-hornfels, and marble. The marble layers provide the best evidence as to the attitude of these rocks, which is vertical or very steeply south-dipping.

The marble, the southernmost unit of the series to crop out in Rock Creek Gorge, is light gray to bluish-white, and for the most part is fine-grained, although coarse-grained layers are included. The calc-hornfels is a more pronouncedly banded rock and includes what originally may have been shaly layers. The rock typically is gray-green to dark green, and according to Rinehart and Ross (1957), the minerals present are: pyroxene, epidote, clinozoisite, a light-colored amphibole (tremolite ?), garnet, wollastonite, quartz, and calcite.

The quartz-sericite hornfels is a dark gray or dark green to black, closely jointed and fine- to medium-grained rock cut by many stringers of quartz. The mineral composition as determined by Rinehart and Ross (1957) is: sericite, biotite, andalusite, quartz, and plagioclase. These rocks weather to various shades of red or dark brown, and bold outcrops are rare, presumably because of the closely spaced joints. Only a thin, stony, reddish-brown soil is developed on these rocks.

The age of these contact-metamorphic rocks is unknown. Rinehart and Ross (1957) believe them to be Late Precambrian or Early Paleozoic on the basis of their geographic position, about midway between rocks of known Late Precambrian and Early Paleozoic age in the White Mountains to the southeast and rocks of Ordovician and Pennsylvanian age in the Sierra Nevada to the west.

Mesozoic Intrusive Rocks

With the exception of the small metamorphic pendants described above and two equally small bodies of diorite and gabbro, all the visible pre-Tertiary rocks are quartz monozonite or closely related variants. The chief areas of outcrop are the entire escarpment of the Sierra Nevada, isolated islandlike areas that are the tops of nearly buried hills projecting through the rhyolite tuff of the Volcanic Tableland, and granitic ridges unroofed through erosion which are exposed on the walls of Rock Creek and Owens gorges.

The age of these intrusive rocks, if they are to be correlated with their petrologic equivalents in the Bishop area immediately to the south, is Cretaceous, according to Rinehart and Ross (1957), on the basis of age determinations made by Larsen and his associates (1954).

QUARTZ DIORITE AND GABBRO

Two very small, isolated bodies of these rocks crop out in the area in (1) the deep defile near the mouth of Rock Creek Canyon, and (2) on the ridge of the Sierra Nevada immediately south of Little Round Valley. Their total areal extent is only about a quarter-section.

The gabbro makes somewhat craggier, darker outcrops and supports a sparser vegetative cover on its thin bouldery soil than the immediately adjacent granitic rocks. Geomorphologically, the principal significance of the gabbro is that boulders of it are common constituents of the gravels surfacing the terraces marginal to the southeastern border of Little Round Valley. Gabbro boulders also make up the bulk of the poorly sorted, till-like, bouldery deposit visible in road cuts along U.S. Highway 395 on the south side of Little Round Valley immediately east of Crooked Creek. The origin of this deposit of large, angular, dominantly gabbro boulders is difficult to understand. On the basis of its advanced state of weathering it may be a till or fluvioglacial deposit of the Sherwin stage.

Quartz diorite is marginal to, and closely associated with, the gabbro. It is a medium-grained rock whose gray groundmass has biotite and hornblende crystals scattered throughout. Very little quartz is present, and most of the feldspar appears to be plagioclase. Bateman, Ericson, and Proctor (1950) give the following percentage composition for similar rocks to the south of this area: quartz, 10–20; potash feldspar, 0–15; plagioclase, 50; biotite, 15; hornblende, 10–15. They also believe that for this part of the Sierra Nevada the order of emplacement was generally from the less to the more siliceous plutonic rocks. The first in order of intrusion here was gabbro, which was followed in sequence by quartz diorite, granodiorite, quartz monzonite, and granite.

GRANITIC ROCKS

The most abundant granitic rock is quartz monzonite, whose distribution is shown on the geologic map (map 1, in pocket). Not only does it form the entire escarpment of the Sierra Nevada, but it very likely underlies most of the Volcanic Tableland as well. It is the only type of bedrock, with the exception of minor pendants of hornfels, exposed in the Owens Gorge on the summits of partly buried ridges projecting into the Bishop tuff and Sherwin till, and encountered in the tunnel.

Quartz monzonite of this area commonly is light gray with a medium- to coarse-grained texture. In porphyritic varieties, orthoclase phenocrysts may range up to 2 cm. in length, and these are a conspicuous feature of the rock. To the quartz monzonite exposed here, Rinehart and Ross (1957) apply the name of Quartz Monzonite of Wheeler Crest, and describe it as having the following percentages of essential minerals: potash feldspar, 20–45; plagioclase feldspar, 20–45; quartz, 20–50; biotite, 1–10; hornblende, trace. As a rule, dark inclusions are rare.

The joint interval ranges from 1 to 10 feet, and outcrops are relatively conspicuous. The summits of partly buried hills projecting through the tuff or glacial till on the Volcanic Tableland commonly are surmounted by rounded granitic knobs and large residual boulders of weathering. Higher slopes of the Sierra Nevada are blanketed with long screes of frost-shattered angular blocks, and rounded forms are uncommon.

Although the quartz monzonite appears to be petrographically similar to the same rock type in the Yosemite Valley (Calkins, 1930), the domes and broad, smooth granitic surfaces of that region are lacking here. The cause is probably related to the local, much smaller joint interval. That this is a tectonically more active area is shown by the multitude of faults, and by the fact that the rock has been shattered into blocks as is clearly demonstrated where it is exposed in the buried hill at Power House No. 1, as well as where it is penetrated by Tunnel No. 1.

Although smaller bodies of granodiorite are associated with the quartz monzonite, they were not mapped separately. One fairly extensive body in the Sierra Nevada is a notably equigranular rock, described by Rinehart and Ross (1957) as the Granodiorite of Rock Creek; this rock crops out along the southwest border of the area, as well as forming the west wall of Rock Creek Canyon. The granodiorite is darker gray than the adjoining quartz monzonite, and it contains relatively less potassium feldspar, more plagioclase, less quartz, and significantly more biotite and hornblende. The joint spacing is closer, and as a consequence the rock fragments more readily to form long scree slopes. This granodiorite is a conspicuous element in the glacial debris that veneers the walls of Rock Creek Canyon and in the stream and alluvial gravels near Toms Place.

TERTIARY (?) VOLCANIC ROCKS

BASALT

This rock, to which a Late Tertiary age was assigned by Gilbert (1941), crops out at only two places in the area: (1) the walls of the Owens Gorge and (2) an isolated outcrop projecting through the Bishop tuff of the Volcanic Tableland a few hundred feet north of the rim of the gorge. It is also encountered underground at a number of places in Tunnel No. 1 and in drill holes along its alignment.

The rock is very dark gray or black on fresh surfaces, but weathers red or brown. Visible minerals are olivine and augite, set in a dense groundmass. Individual flows are thin where they can be seen in the walls of the gorge; few appear to be more than 40 or 50 feet thick. The tops are scoriaceous, and the bases are commonly brecciated. The thin interbeds of pyroclastic basalt weather readily to make niches separated by ledges of more resistant basalt flows.

The canyon section demonstrates that the basalt incompletely buried a terrane of moderate relief. The basalt is more than 600 feet thick, since its base is unexposed in the part of the Owens Gorge which trends southeast and is this deep here. The basalt thins to 5–10 feet on the summit of the buried granite hill at Power House No. 1. Since this thinning occurs within a horizontal distance of about 2,000 feet, the original slope of the buried hill was approximately 1,500 feet per mile, assuming no great amount of pre-Sherwin deformation for this particular section.

No evidence is available within the area mapped to establish the age of the basalt. It rests on weathered quartz monzonite and is overlain unconformably by Quaternary rhyolite tuff in the central part of the gorge and by Sherwin till in the southern section in the vicinity of Power House No. 1. In the tunnel it is universally covered by Sherwin till.

The basalt is broken by faults of greater throw than those that cut the overlying Quaternary rocks. Some of these faults have been revived, and offset the superjacent rhyolite tuff with smaller displacement than they do the basalt, whereas others have seemingly remained inactive. In any event, an erosion surface of moderate relief beveled the faulted surface of the basalt before the Middle and Late Pleistocene volcanic and glacial deposits accumulated.

A Late Tertiary age appears plausible for the basalt, according to Gilbert (1941), because of its stratigraphic position, its greater deformation than the overlying rocks, and its truncation before the mid-Pleistocene, although locally, there is nothing to indicate that these basaltic tuffs and flows are not Early Pleistocene. A nearly similar, strong faulted basalt resting directly on bedrock is found 3 miles west of here on the shoulder of McGee Mountain, where it is overlain by till of the McGee glacial stage which precedes the Sherwin.

Quaternary Volcanic and Sedimentary Rocks

The Quaternary rocks are of central importance in any explanation of the origin of Rock Creek and Owens gorges, and of the landscape of which these canyons are a part. To a considerable extent, the landforms of the region are constructional, and many of them preserve the original appearance associated with volcanic, lacustrine, or glacial deposits, such as glacial moraines and gravel-capped stream and lake terraces. Among the rock units of Quaternary age are the tills of three glacial stages and an accumulation of rhyolite tuff which is more than 800 feet thick. These Quaternary rocks of such widely diverse origin are discussed in the order of their relative age from older to younger in the sections to follow.

SHERWIN TILL

The oldest unquestionable Pleistocene formation of the area is the Sherwin till (Blackwelder, 1931), whose type locality is Sherwin Hill near the southern boundary of the area. A portion of the till rests unconformably on pre-Tertiary crystalline rocks, another part on Late Tertiary (?) basalt. It is partly buried by the next younger rock unit in the stratigraphic succession, the Bishop tuff. The Sherwin is the second in the sequence of four major glacial tills found on the eastern slope of the Sierra Nevada (Blackwelder, 1931). The oldest, or McGee stage, has its type locality on the northern shoulder of McGee Mountain, 4 miles west of the area mapped and about 3,000 feet above the floor of Long Valley.

The greatest expanse of Sherwin till is in the broad lobe east of Whisky Canyon. It extends eastward along both sides of Rock Creek Gorge, in whose walls is exposed a thickness of about 450 feet of glacial detritus of this stage. A thin band of till crops out in the walls of Owens Gorge on both flanks of the buried ridge near Power House No. 1; here the till rests on granitic rocks and patches of basalt and is overlain in turn by rhyolite tuff. The same relationships are found in Tunnel No. 1 where about 11,000 lineal feet of till are encountered and here have a thickness of about 400 feet, as shown in drill holes along the tunnel alignment.

Exposures in the walls of Rock Creek Gorge and road cuts along Highway 395 leave little doubt as to the glacial origin of the Sherwin till. The formation consists of a jumble of weathered boulders, cobbles, and gravel in a sandy and silty matrix. Some of the boulders are more than 10 feet across, and all are of rock types that crop out in the immediately adjacent Sierra Nevada. Many of the boulders are angular and some are strongly faceted.

The map pattern of the till further substantiates its glacial origin. The geologic map (map 1, in pocket) shows that this deposit radiates outward from a high point on the south side of present-day Rock Creek Canyon. However, unlike an alluvial fan, the surface of the Sherwin till is corrugated by radial ridges, the eroded remnants of lateral moraines. Some of the fault scarps that once interrupted the surface of the till are now planed off by erosion. An outstanding example is provided by the fault that is plainly visible in the walls of Rock Creek Gorge a quarter of a mile north of where the old alignment of Highway 395 crosses the creek. This fault had a throw of at least 300 feet, and today the ground surface on the upthrown side has been beveled by erosion to the same level as the downthrown. In addition, the blanket of rhyolite tuff which presumably once covered the Sherwin till as far west as the mouth of Whisky Canyon has been stripped off by erosion.

The age of the Sherwin till relative to the overlying Bishop tuff, the most extensive formation of the area, at first proved to be equivocal. For example, it was Blackwelder's (1931) belief that the till rested on the Bishop tuff. Gilbert (1938) noted the narrow band of till cropping out under the Bishop tuff in the walls of the Owens Gorge, and recognized what I am certain is the correct relationship, that the Bishop tuff is the younger, and overlies the Sherwin till.

That Gilbert's interpretation is true is further supported by the data provided by Tunnel No. 1 and the accompanying drill holes. The cross section (fig. 1, in pocket) drawn along the tunnel line shows that the Bishop tuff rests on a thick accumulation of till. The glacial deposits are within about 100 feet of the surface at Drill Hole 1-C, which is immediately east of the surface exposure of till most distant from the Sierra Nevada. The geologic map (map 1) shows that this drill hole is only a short distance east of this last surface exposure and about 2,000 feet west of the outcrop of till in the Owens Gorge. The hole intersects the till surface at the expectable depth on a line connecting these two occurrences.

Another confirmation of the relationship between the two formations is provided by a recently completed road cut near Toms Place on the new route of Highway 395.[1] Here the pumice layer at the base of the Bishop tuff can be seen resting with a sharp contact on the boulders and cobbles of the Sherwin till (pl. 38, *b*).

The purpose of this lengthy discussion of the contact relationships of these units is to correct the error in my interpretation of the relative age of the two formations in the June Lake area, 30 miles northwest (Putnam, 1949). There the Bishop tuff overlies a till which was encountered underground in the Mono Craters Tunnel and also on the surface of the Aeolian Buttes. At that time I believed the till to be a pre-Sherwin glacial deposit and gave the name Aeolian Buttes till to it, thinking it to be the equivalent in age of the McGee till of Blackwelder. The significance of this misinterpretation is that four glacial stages, including the much younger Tahoe and Tioga tills, were identified in the country east of the Sierra Nevada, and the Bishop tuff was placed between stages I and II, rather than II and III, as can be demonstrated here. In other words, no unequivocal example of deposits of the McGee glacial stage is presently identifiable in either the June Lake or Owens Gorge areas.

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[1] This new alignment (1957) joins the old about 1 mile east of Toms Place, where the new highway crosses Rock Creek and then follows a course roughly parallel to the C.E.P. transmission line across the surface of the Volcanic Tableland. The hazardous descent of the old road into Rock Creek and the interminable switchbacks up the Sherwin Grade are things of the past and probably will not be missed, except by those to whom they provided an adventurous break in the tedium of a long drive up the Owens Valley.

In light of the evidence provided by the Owens Gorge which demonstrates that the Sherwin till is pre- rather than post-Bishop tuff, only three major glacial stages are recognized, and the name Aeolian Buttes till should be considered invalid as representing an earlier Pleistocene, pre-Sherwin glacial stage. If the name is to be retained at all, it should be regarded as having significance only in the Mono Basin as a probable equivalent of the more widely recognized Sherwin glacial stage.

BISHOP TUFF

The Bishop tuff has the greatest areal extent of any formation mapped (map 1). It is the dominant element in the landscape of the Volcanic Tableland, and is also the principal rock exposed in the walls of the deep Owens River Gorge.

The formation for the most part is a rhyolitic ignimbrite and consists of layers of pumice, sillar, and welded tuff. The maximum thickness visible in the Owens Gorge, without having the base exposed, is 700 feet. The 650 feet penetrated in Drill Hole 1-X is the maximum thickness encountered on the alignment of Tunnel No. 1. That the thickness of the Bishop tuff is anything but constant is apparent from the section exposed in the walls of the Owens Gorge, where it can be seen that the tuff was deposited on the slopes of a now buried granite ridge and thins from a maximum of 700 feet in the former valley to a minimum of perhaps 50 feet on the ridge summit.

The petrology and petrography of the Bishop tuff have been described by Gilbert (1938), and, as pointed out by him, it very likely was emplaced by a succession of *nuées ardentes* erupted over a wide area from many fissures. The tuff has an areal distribution extending from far down the Owens Valley to the south to the Mono Basin on the north, a distance of about 70 miles. The area covered by the Bishop tuff, according to Gilbert, exclusive of the portion concealed beneath the alluvium of such troughs as Long Valley and Owens Valley, is 350 miles; the total with the concealed sections included is perhaps closer to 450. Assuming an average thickness of 400–500 feet, this yields a volume of approximately 35 cubic miles of erupted material.

The composition of the tuff is not uniform from top to bottom. In the segment of the Owens Gorge west of the buried granite ridges (map 1) at least five distinct interbedded pumice and tuff beds can be recognized. Almost everywhere at the base of the Bishop tuff is a white or pink layer of pumice, which in Tunnel No. 1 is at least 100 feet thick. This layer consists of a matrix of glassy dust with pumice fragments embedded in it which range from 8 inches to 1 foot across. The basal pumice is well exposed in the wave-cut cliffs on the eastern shore of Lake Crowley, on the long grade on Highway 395 west of Little Round Valley, and in road cuts along the new highway southeast of Toms Place where it rests on the Sherwin till with a knife-sharp contact.

In general, only a few layers of welded tuff are interbedded with pumice near the base of the formation. As a rule, true welded tuffs seem less common here than in the Mono Basin farther north. According to Rinehart and Ross (1957), most of the Bishop tuff in the Owens Gorge section is best described as a sillar because the induration of the tuff appears to be the result of partial recrystallization, rather than of softening, flowage, and recrystallization under heat and load. However, some of the layers encountered near the base of the formation, about 6,000 feet in from the north portal of Tunnel No. 1, are true welded tuffs with the characteristic collapsed and elongated pumice fragments.

As seen underground, unweathered tuff commonly is dark steel gray. At the surface it weathers to light gray, pink, brown, and occasionally purple. Indurated layers are broken by mural joints, and some beds are characterized by conspicuous columnar joints. In a few places these radiate from a common point, and such rosettes appear to be located underneath the low, conical hillocks that are a typical feature of the Volcanic Tableland south of Sherwin Hill since one of these, which would appear to be a representative example (pl. 35, *b*), has been cut in half by the Owens River near Power House No. 2. Such radial structures very probably mark places where hot gases continued to escape for some time following the emplacement of the tuff.

In addition to the innumerable pumice fragments, both collapsed and whole, the Bishop tuff includes fragments of granitic rocks, hornfels, and basalt. Many of these are small, but a few are as large as a foot across, and almost all are angular. Most are locally derived, which is to say that where the tuff buries a granitic terrane, the fragments are granitic; where the bedrock is hornfels, this constitutes most of the fragments.

The most striking aspect of the Bishop tuff on the Volcanic Tableland is its rough and craggy surface. Seen from afar, the plateau appears as a nearly level forested plain. A closer view shows a host of crags and pillars, many with nearly vertical walls. These red-brown pinnacles, resembling ruined towers, are separated from one another by wide swales floored with light gray pumice. This complex pattern of crags and pinnacles is largely confined to the higher portion of the Volcanic Tableland which supports a parklike stand of Jeffery pine. Below an altitude of 6,500 feet, where the forest gives way to juniper and sage, the Bishop tuff makes a more continuously sloping surface, gashed by narrow arroyos, and diversified by low conical hillocks, which very likely were the sites of former gas vents. The presence of these mounds is an indication that the configuration of much of the present-day lower part of the surface of the Volcanic Tableland is the result of stripping, and also an indication that these cones are residual hills which owe their preservation to their higher degree of induration and, hence, their greater resistance to erosion.

What the explanation may be for the pronounced difference in topographic expression involving the same rock type—the Bishop tuff—on two contiguous parts of the Volcanic Tableland is not immediately apparent. It may be partly the result of a more closely spaced fracture pattern in these brittle rocks underlying the higher part of the Volcanic Tableland near Toms Place. On the other hand, the control appears to be climatic in part, and may be related to heavier snowfall, or more effective frost-shattering at higher altitudes. The relationship between the differing topographic forms on the same rock and the lower limit of the pine forest is so close as to appear to be more than fortuitous.

The basal pumice layer of the Bishop tuff has not been mapped separately by me, although in the northwestern part of the area it is a thick and widespread unit that makes conspicuous white sea cliffs bordering the eastern side of Lake Crowley. According to Rinehart and Ross (1957), the pumice blanket extends north of the mapped area, and has for its southern boundary in this area the clifflike terminal outcrop of the Bishop tuff at the rim of the Volcanic Tableland, under which the pumice apparently passes.

Rinehart and Ross (1957) assign a Tertiary age to the thick section of pumice and obsidian which makes up the main body of Glass Mountain, an imposing ridge 11,127 feet high and rising 2,100 feet above Long Valley about 10 miles north. They also point out that the pumice underlying the Bishop tuff east of Lake Crowley contains abundant fragments of perlitic glass and obsidian, whereas the basal pumice layer south of Lake Crowley does not contain these obsidian fragments. However, they also indicate that "outcrops of pumice and glass near the Bishop tuff almost certainly contain admixed pumice of the same age as the Bishop tuff."

My opinion is that at least the upper part of the pumice layer in the small area east of Lake Crowley is equivalent to the basal member of the Bishop tuff elsewhere in the area mapped. For this reason I have not differentiated the two formations on the geologic map (map 1) as have Rinehart and Ross (1957), who correlated the pumice with the Glass Mountain rhyolitic sequence farther north, but rather have included it with the Bishop tuff immediately adjacent to the south which has a clearly established Late Pleistocene age.

A Potassium-Argon date of 870,000 years has recently been determined for a sample of the Bishop tuff (Evernden *et al.,* 1957). This age seems too high to me in view of the recency of the deposit in terms of the glacial sequence and the erosional and tectonic history of this part of the Sierra Nevada. Future work probably will confirm or disprove this date, but at the moment it seems too remote a time for the eruption of the tuff. Field evidence strongly demonstrates that this event occurred in the latter half, rather than in the earlier part of the Pleistocene epoch.

In summary, the Bishop tuff is a thick accumulation of rhyolitic pumice, sillar, and welded tuff, the product of a succession of *nuée ardente* eruptions. The thicker layers were compressed and welded, and in the later phases of consolidation the loss of heat was localized, with the formation of columnar and radial joints and indurated zones as a result.

TAHOE TILL

Moraines of the Tahoe glacial stage (Blackwelder, 1931) flank Rock Creek Canyon in the Sierra Nevada west of Highway 395. The geologic map (map 1) shows a rather unusual distribution for these moraines. The glacier was divided by the granite hill immediately south of the present-day canyon with the northern arm of the glacier following the course of the existing Rock Creek Canyon and the southern arm occupying Whisky Canyon. The northern fork of the glacier was more effective in excavating its trough than was the southern. Judging from the extent to which Tahoe till blankets the walls, the ice deepened the canyon to about the present-day altitude of the canyon floor of 8,000 feet from a Sherwin depth of 8,200 feet.

The history of the Whisky Canyon or southern branch is less clear. The Tahoe ice seemingly followed approximately the same route as the preceding Sherwin glacier. However, it failed to excavate as deep a canyon as the northern arm. Tahoe and Sherwin tills are both present in formerly ice-occupied Whisky Canyon, and have not been stripped away by postglacial stream erosion, as they have been in Rock Creek Canyon immediately adjacent to the north.

The two tills may be distinguished by the degree of preservation of the original glacial landforms. No terminal moraines have persisted from either stage. Tahoe lateral moraines of the Rock Creek Canyon arm are nested inside the present canyon, and, in general, are more sharply crested and clearly defined than are the more blurred Sherwin moraines outside the canyon walls.

Use of the relative degree of preservation of the original constructional landforms is a less certain criterion when applied to the moraines of the Whisky Canyon branch. The Tahoe morainal ridges are relatively more sharply crested only near the junction with Rock Creek Canyon as compared with the more rounded and subdued Sherwin moraines. The difference is less marked downslope toward Highway 395, and at a point about 0.8 of a mile west of the highway the Sherwin and Tahoe deposits can no longer be clearly separated. The contact between the two tills as shown on the geologic map is a liberal interpretation of the limit of Tahoe advance. A more conservative estimate might place its limit nearer the head of Whisky Canyon, approximately 0.5 of a mile from the junction with the main trunk glacier in Rock Creek Canyon.

I did not make use of the Granite-Weathering-Ratio of Blackwelder (1931) at the time I mapped the area, because I was not convinced of its value in discriminating between these tills. Since learning of the success that Birman (1957) had, with his modification of the original system, in distinguishing among glacial deposits of several stages in the central and western Sierra Nevada, I believe that it might also be employed successfully here.

TIOGA TILL

Till of this last Sierran glacial stage (Blackwelder, 1931) cannot be identified here with the confidence that it can elsewhere in the general region east of the central Sierra Nevada divide. The usual bases for recognition are that (1) Tioga moraines are clustered inside the higher Tahoe laterals, and (2) Tioga terminal moraines are preserved, whereas Tahoe terminals are not. Although no Tioga terminal moraines are to be found in the granite narrows of Rock Creek Canyon, this is owing to local circumstances.

The small area of Tioga till in Rock Creek Canyon (map 1, in pocket) represents several relatively fresh-looking lateral moraines when compared with the higher Tahoe moraines within which they are nested. This inferred lower limit of Tioga glaciation coincides approximately with the upstream entrance of the narrow, rock-walled defile near the mouth of Rock Creek Canyon. The latter also marks the point where there is a pronounced quickening of the stream gradient. A similar abrupt change also characterizes the lower limit of Tioga glaciation in Leevining Canyon (Putnam, 1950), 35 miles northwest.

LAKE BEDS

Deposits of Pleistocene Long Valley Lake (Mayo, 1934) cap a succession of benches cut on Bishop tuff and pumice on both shores of Lake Crowley immediately upstream from Owens Gorge in the neighborhood of Long Valley Dam. That terraces are best developed on the eastern side is very likely owing to the fact that at the time of their cutting this was the leeward shore of the lake, as it is today, and also the side where readily eroded pumice deposits are most widespread. Owing to strong waves and weak rocks, the maximum width of the terrace treads is about a mile in pumice on the east shore, as compared with a half a mile or less where these benches were cut in the more resistant Bishop tuff on the western shore.

Lake beds on the east side of Lake Crowley have a maximum thickness of approximately 100 feet, thinning to a feather edge at the highest shore line, which is at an altitude of 7,000–7,020 feet. The lake beds are layers of sand and gravel. Most of the clasts are 1 inch or less in diameter, although a few boulders up to 10 inches across were noted. The lake deposits are prevailingly dark because of the preponderance of gray or black hornfels fragments. Together with other metamorphic rocks, they have been transported a minimum distance of 4 or 5 miles across Long Valley from their source in the Sierra Nevada. Granitic rocks are less common, but they usually make the larger clasts, many of which are angular and strongly faceted. Pebbles of obsidian also are in the gravel, and very likely had their source in Glass Mountain, about 10 miles to the north, and from where they were transported by longshore currents. A few gravel layers are moderately indurated with calcareous cement, and these stand out as ledges in contrast to the unlithified sandy layers with which they are intercalated.

Only a few discontinuous patches of lake deposits are exposed on the south side of Lake Crowley near Long Valley Dam. This area generally is one of craggy pinnacles and closed basins, the same sort of topography that is so characteristic of the Bishop tuff on the higher parts of the Volcanic Tableland, although here it is well below the highest lake level. This topography contrasts strongly with the north side of Lake Crowley where lake beds rest on a gently sloping surface beveled across what appear to be rocks of nearly the same resistance to erosion. One explanation of this differing resistance to erosion may be related to more effective work of waves and currents on the leeward side of the lake, especially when they were directed against a projecting headland of friable pumice protected by only a thin capping of tuff.

The age of the lake beds cannot be established with certainty, although there is no doubt that they are post-Bishop tuff, since they rest on its truncated surface. Mayo (1934) believed that the maximum extent of Pleistocene Long Valley Lake was essentially synchronous with the Tahoe glacial stage. This is very likely true, but their relative ages cannot be determined here because at no place within the area mapped do shore lines of Long Valley Lake cut Tahoe moraines.

OLDER ALLUVIUM, STREAM TERRACES, INACTIVE FANS AND CONES

Stream terraces can be recognized in Rock Creek Gorge as far south as Sherwin Hill. They commonly are covered with cobbles and gravel derived from the glacial till. Downstream, from about the junction of Rock Creek and Whisky Canyon, the terraces are inclined in the same direction as the present stream and seemingly with about the same gradient. Upstream from the junction, the terraces slope in a direction opposite to the present longitudinal profile of the stream. Two particularly well-developed, north-sloping terraces cap the prominent low, rounded hills of Sherwin till on the east side of Rock Creek, almost opposite the mouth of Whisky Canyon. These reverse-sloping terraces probably were cut at a time when Rock Creek drained northward into Long Valley, before it was captured by the headward growth of the segment now occupying Rock Creek Gorge, and as a result was then diverted southward to the Owens Valley.

Several types of older alluvium are present in the area. They comprise gravel-covered terraces marginal to entrenched stream channels or older alluvial fans and screes now being dissected by the streams crossing them. The distribution of these geologically recent, but presently inactive, deposits is shown on the geologic map (map 1). Very likely they record the latest stages in the uplift of the Sierra Nevada, and very possibly they also bear the imprint of climatic fluctuations in the very recent geologic past.

At least two Late Quaternary deposits are present in Little Round Valley: (1) the sediments that constitute the nearly flat, marshy floor of the grassy meadow which is graded to the present base level of Long Valley, and (2) a series of benches and boulder- and gravel-capped terraces cut in the Bishop tuff, chiefly along the south side of Little Round Valley, which are graded to shoulders on either side of the narrow, slotlike canyon of Crooked Creek connecting Little Round Valley with Lake Crowley. The abrupt change from a widely flaring upper canyon to a lower canyon with a vertical-sided cross profile occurs at about 7,000 feet, which corresponds to the high stand of Pleistocene Long Valley Lake. Since the dissected terraces of Little Round Valley are graded to this level, they quite likely were contemporaneous with the lake maximum.

Other examples of older alluvium are the long screes of boulders and slide rocks on the marginal slope of the Sierra Nevada, especially in the reëntrant south of Little Round Valley, and also to the west of Sherwin Hill. These older talus slopes and rock streams are incised by gullies scored in the Sierran escarpment, and currently, during wet weather, torrents are engaged in constructing a new set of debris cones and alluvial fans. Some of the older fans have been beheaded by faulting, notably in the Little Round Valley area, whereas in others the cause for the regrading of these mountain front arroyos is obscure. It may be owing to the continuing intermittent uplift of the range, to recent climatic changes, to the lowering of local base level through the downcutting of Rock Creek, to the draining of Pleistocene Long Valley Lake, or to the normal regrading that goes on in any fan-building stream. Very likely the explanation is a combination of several of these factors.

YOUNGER ALLUVIUM, ACTIVE FANS AND CONES

The principal Recent and Late Pleistocene sediments are newly deposited lake beds, such as those adjacent to Lake Crowley, alluvial fans and talus cones, stream gravels, and local accumulations of pumice in closed depressions, especially on the craggy portion of the Volcanic Tableland.

The largest alluvial fan is the one constructed by Rock Creek where it leaves its canyon in the Sierra Nevada and before it makes a 90° change in course at Toms Place to begin its descent into Rock Creek Gorge. This fan is a mile long, has a gradient of 450 feet per mile, and is surfaced with gravel and boulders up to 5 feet in diameter. The fan drains two ways: (1) to the north, by a subsidiary stream that crosses the meadowland of Little Round Valley to Long Valley, joining the Owens River north of the Volcanic Tableland, and (2) to the south, by way of the main stream of Rock Creek via its Gorge, and ultimately joining the Owens River south of the Volcanic Tableland in the Owens Valley west of Bishop (see fig. 3 showing drainage evolution). This dual drainage is less well established now than it must have been in the very recent geologic past. Today the main stream is incised below the surface of the fan, probably chiefly as the result of the wave of rejuvenation that has advanced up Rock Creek Gorge. Another factor reducing the effectiveness of the north-flowing distributaries is that much of their water is now diverted to irrigate Little Round Valley.

STRUCTURE

PRE-TERTIARY STRUCTURES

The evidence available in this small area is inadequate to unravel the structure of the pre-Tertiary rocks. The same circumstances seemingly apply here locally as are cited by Gilbert (1941) for the general region east of the Sierra Nevada and southeast of Mono Lake: "The oldest rocks exposed in this area are all metamorphosed sediments—marble, mica schists, quartzite and calc-silicate hornfels being the most common. These are intruded by granitic rocks so widely exposed by erosion that the metasediments are numerous small patches of obscure structure. Numerous steep dips prove that they have been intensely folded."

BASIN AND RANGE FAULTS

The structures of chief concern here are the Late Cenozoic faults that cut all the rocks of the region, including Late Pleistocene moraines and Recent talus cones and alluvium. The geologic map and cross sections (map 1 and fig. 1, in pocket) make the following facts evident: (1) most of the faults are essentially straight, (2) they dip at high angles and do not appreciably offset one another, and (3) the amount of throw decreases with the recency of the deposit that is cut (Late Pleistocene moraines and talus deposits show the least, and pre-Pleistocene formations, such as the basalt in the Owens Gorge, the most).

Deciding which linear features are faults, and which are not, is not easy. Aerial photographs show scores of lineaments that are best developed in the Bishop tuff and to a lesser degree in the Sierran granites. What weight to assign the various elements of this fracture pattern is dependent very largely on the prejudices of the photo-interpreter. Few of these lines are actually visible on the ground, or if they are recognizable at one place, they cannot be followed far. The geologic map gives a relatively conservative interpretation, for most of the faults shown have observable offsets in the bedrock, adequate surface expression in the form of low scarps, aligned reaches in stream courses, or else make depressions and low scarps crossing moraines and older gravel deposits and alluvial fans. Doubtless many more faults exist than are shown, and their seeming concentration in the Bishop tuff is more apparent than real, since it very likely is a consequence of their easier identification in these relatively flat-lying brittle rocks, rather than of their relative infrequency elsewhere. The geologic map also brings out the close resemblance of the fault system to a large-scale joint pattern, a relationship that was considered especially significant by Gilbert (1941). He points out that a high correlation exists between the strikes of faults and those of joints throughout the region east of the Sierra Nevada.

That the faults have steep dips is shown not only by their straight alignment where they cross topography with strong relief, but most tellingly through the evidence provided by Tunnel No. 1. Here the fault with the largest measured displacement is encountered about 8,800 feet in from South Portal. This fault, with a dip of about 65°, brings quartz monzonite to the surface, and has developed a possible throw of about 500 feet since the accumulation of the Bishop tuff—the youngest formation which it cuts.

Faulting has been active in the region throughout a long period of time. As mentioned before, the amount of displacement on many of the faults diminishes with the age of the deposit that is cut; for example, Sherwin moraines are offset more than Tahoe, and Tioga moraines are affected least of all. The basalt of the Owens Gorge shows a greater offset than the overlying Bishop tuff. Most of the faults cutting the Bishop tuff appear to have a throw of less than 150 feet.

As stated by Gilbert (1941), "Hulin (1931, p. 307) has suggested the term 'subsequent fault' for displacement controlled by previously existing planes of weakness." The local evidence seemingly indicates that this situation holds for most of the faults that cut the more recent formations.

Gilbert also points out in the same paper (1941):

> (3) Southeast of Mono Lake, the rocks displaced are primarily granitic with a thin capping of extrusive rocks. The effect of these lavas upon the faulting could only have an unimportant very shallow control. Hence the controlling element must be heterogeneity within the plutonic and metamorphic rocks. The irregular outlines of these intrusions do not control the faulting, for the fault pattern has no apparent relation to their contacts. In a structural sense, joints and earlier faults in the plutonic rocks are certainly a secondary feature of heterogeneity; probably these fractures defined planes of relative weakness followed by later normal faults, for, in a region literally shattered by joints and displaced along later normal faults, it seems reasonable that the faults should utilize earlier fractures instead of ignoring them.
>
> (4) If they controlled the faults the joints necessarily existed prior to the displacements. They are older than the faults in this region, for the weathering of the old erosion surface, in places covered by Tertiary lavas and displaced by the faults has gone deep along these joints isolating many large residual boulders of granitic rock.

Gilbert demonstrates that a reasonably high correlation (0.61) exists between the strike of joints in the crystalline rocks and the regional pattern of the fault mosaic for the country southeast of Mono Lake. The same sort of control very likely operates here, and may explain in part the large angles of intersection of the dominant fault systems. One exception may be the closely spaced fracture system in the Bishop tuff, part of which may be the result of contraction on cooling. However, the fact that fractures originating in the intrusive and metamorphic rocks have been transmitted to the Bishop tuff through the underlying unconsolidated Sherwin till is abundantly demonstrated by exposures in Tunnel No. 1 where many faults, some with wide gouge zones, cut the till.

At what time the Sierra Nevada reached its present altitude is difficult to say. Certainly it was a region of moderate to strong relief by the Sherwin glacial stage, which Blackwelder (1931) tentatively correlated with the Kansan stage. Not only was the Sherwin a far more extensive glaciation than the Tahoe or Tioga, but blocks of granite in this older till are equally large, and have been transported a minimum distance of 3 miles farther from the mountain front than the easternmost advance of Tahoe ice. The Sherwin till has been displaced an approximate minimum of 500 feet on the Volcanic Tableland, as shown by the evidence provided in Tunnel No. 1, and 300 feet in the section visible in Rock Creek Gorge.

McGee glacial till, the earliest in this area, caps the eastern shoulder of McGee Mountain, about 3 miles west of the area mapped, and is truncated abruptly at the upper edge of the bold Sierran escarpment. If the continuation of the McGee till has been faulted down beneath the floor of Long Valley at the base of the range, then there has been a minimum uplift of 3,000 feet along the eastern margin of the Sierra Nevada in the Late Pleistocene, since this is the least possible difference in altitude between the McGee till on McGee Mountain and its downfaulted counterpart below the floor of Long Valley. Actually, the displacement almost certainly exceeds 3,000 feet, because the downdropped segment of McGee till probably is buried under an indeterminate thickness of Sherwin till or related glacio-fluviatile deposits, Bishop tuff, glacio-fluviatile deposits of the Tahoe stage, and their lacustrine equivalents that accumulated on the floor of Pleistocene Long Valley Lake. That these Quaternary volcanic and sedimentary rocks, all younger than the McGee glacial stage, are at least 1,000 feet thick here, at the margin of the basin, seems reasonable; this would then make the displacement along the eastern face of the Sierra Nevada amount to approximately 4,000 feet since the McGee glacial stage.

That Long Valley is a subsiding trough bordered by faults was first recognized by Mayo (1934). His interpretation has been substantiated recently by the results of a gravimetric survey conducted by the U.S. Geological Survey which shows that the bedrock floor of Long Valley is buried under a cover of 12,000 feet of less dense material, according to Pakiser and Kane (1956). This figure seems high to me, although I have no way to check my intuition, since no drill-hole data are available. I suspect that more pumice may be present in the valley fill than may have been assumed, and because of its low density may have had the effect of giving the impression of an apparently greater depression of the valley floor than actually may have occurred.

Nonetheless, Pakiser's and Kane's interpretation agrees with my opinion that one of the important fault systems in the area trends N. 35° E. paralleling the low escarpment east of Lake Crowley, separating the craggy surface of the Bishop tuff of the Volcanic Tableland from the more subdued terrain of the lake terraces cut across the underlying pumice. This fault is upthrown to the southeast, and possibly is responsible, together with larger related faults to the northwest with similar displacements, for the elevation of the granitic ridge, thinly veneered with Bishop tuff, connecting Wheeler Crest to the south with the Benton Range to the north. Gravimetric data indicate that this fault and its buried counterparts are steeply dipping to the north, and that the deepest part of Long Valley trough is immediately adjacent to them beneath the waters of Lake Crowley. Unquestionably, these faults played an important role in the elevation of the ridge, now the Volcanic Tableland, that separates Long Valley from the Owens Valley, the ridge being the barrier responsible for impounding the waters of Long Valley Lake.

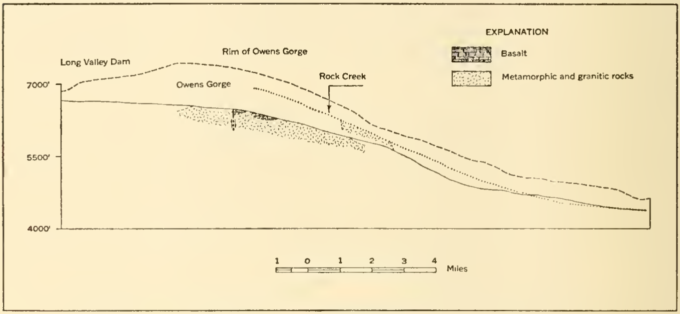

Fig. 2. Longitudinal profiles of parts of Rock Creek and Owens River gorges.

Local evidence indicates rather convincingly that a large share of the uplift of the Sierra Nevada was achieved before the Sherwin glacial stage. The broad, terracelike benches along the Sierran front at altitudes of 7,800–8,000 feet in the vicinity of the mouth of Rock Creek very likely mark stages in the upward growth of the range. Their true significance is not immediately apparent, but they may be pedimentlike surfaces graded to temporary local base levels during times of relative still-stand in the uplift of the mountains.

That faulting is not solely responsible for the full heights to which the Sierra Nevada and Volcanic Tableland rise above the Owens Valley is shown by the degree to which the Bishop tuff has been arched. North of the Owens Gorge the Bishop tuff appears to have a gentle regional dip to the south and southeast. Marginal to the Sierra Nevada the dip is more difficult to determine because of the larger number of faults and their seemingly larger displacement, but it is almost certainly away from the range and toward the Owens Gorge. Along the southeastern margin of the Volcanic Tableland the regional dip of the Bishop tuff is southeast toward the Owens Valley, and there appears to be little doubt that a large measure of the 3,000-foot difference in altitude between the tableland and the valley is the result of warping. This is also the opinion of Rinehart and Ross (1957) who say: "Warping is shown by a profile [reproduced here in modified form as fig. 2] constructed along Owens River Gorge from Crowley Dam to the confluence with Rock Creek in the Mt. Tom quadrangle, adjacent on the south. The profile is markedly convex upward, indicating that the Bishop tuff has been arched since the overflow of ancient Long Valley Lake. The high point shown on the profile of the rim of the gorge could not have been the point of the initial spillover because lake terraces extend less than half a mile east of the dam, whereas the present high point is more than 3 miles east of the terraces. The profile of Rock Creek appears to be normally concave upward and is in marked contrast to the profile of the Owens River."

In my opinion, the convex profile of the rim of the Owens Gorge (fig. 2) is of much greater significance as evidence of Late Pleistocene warping of the Volcanic Tableland than the convex longitudinal profile of the Owens River. The position of the knickpoint, or inflection in its course, is too nearly coincident with the downstream limit of the outcrop of granitic rocks in the canyon floor for the association to be wholly fortuitous. In other words, the granitic rocks have acted as a sill while the less resistant Bishop tuff on the downstream side has been removed at a relatively more rapid rate.

Among the reasons why Rock Creek does not appear to have a convex profile may be the relatively narrower width of the granite outcrop as compared to that of Owens Gorge, as well as the fact that the granite here appears to be more shattered by faults and joints, and also that this outcropping ledge includes a section of marble and hornfels which may not be significantly more resistant to erosion than the immediately adjacent Bishop tuff.

DRAINAGE EVOLUTION

The chief reason for undertaking this study was to work out the evolutionary history of the drainage systems of Rock Creek and the Owens River, and their relationship to the volcanic, glacial, and tectonic history of the adjacent Sierra Nevada.

The present drainage pattern of these streams in relation to the inferred stages of their past history is shown on the accompanying sketch maps in figure 3. The Owens River now connects Long Valley (average altitude, 6,900 feet) with the Owens Valley (average altitude, 4,000 feet) by a gorge 900 feet deep cut across the Volcanic Tableland. Rock Creek follows a less direct course. It flows in a deep canyon excavated in the granitic rocks of the Sierra Nevada, crosses an alluvial fan of its own construction at the base of the range, and then makes a right-angle bend where it commences its descent to the Owens Valley by means of a 700-foot gorge roughly paralleling the larger Owens Gorge.

Pre-Tahoe Drainage Pattern

The earliest relevant event bearing on the history of these streams was the eruption of the Bishop tuff. Following the emplacement of the tuff, the faulting that downdropped Long Valley trough between the Sierra Nevada and the Glass Mountain Range was also responsible for the elevation of the Volcanic Tableland at the southern end of the valley, thus providing a barrier for impounding the waters of Long Valley Lake.

Formation of the fault trough and the lake, whose upper shore line is preserved

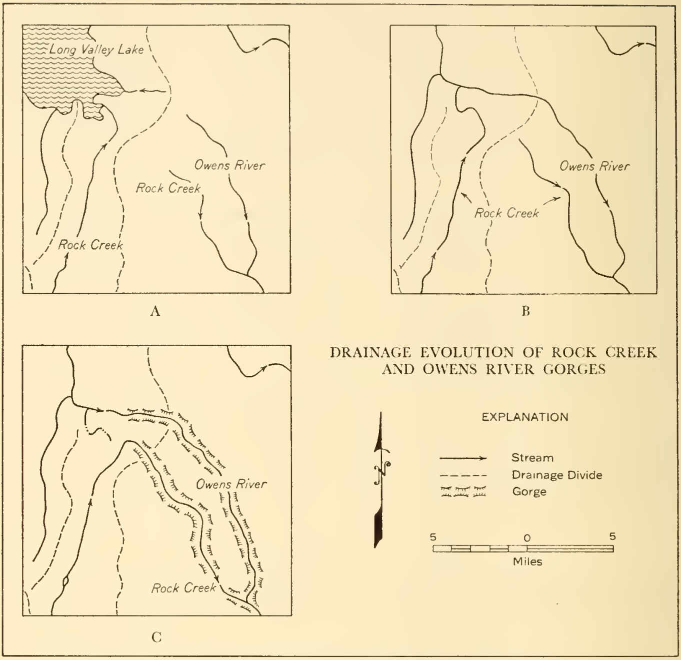

Fig. 3. Drainage evolution of Rock Creek and Owens River gorges.

at an altitude of about 7,000 feet, must have preceded the major advance of Tahoe ice. Whether or not the lake had an outlet in the beginning of its history is not known; at least no spillway is visible today at an altitude of 7,000 feet anywhere on the existing basin rim. Streams draining the Volcanic Tableland flowed south to the Owens Valley or north to Long Valley away from the drainage divide, whose location is shown in figure 3, *A*. The course of Rock Creek was then northward to Long Valley via Little Round Valley because an avenue of escape southward was blocked by the great lobe of Sherwin till fanning outward from Whisky Canyon which deposit in turn is overlain to the east by the even more extensive barrier of Bishop tuff.

That the pre-Tahoe course of Rock Creek was northward to Long Valley is shown by (1) the northerly inclination of stream terraces bordering its present-day valley from the mouth of Whisky Canyon to Little Round Valley, which is opposite to the contemporary gradient of this south-flowing stream, and (2) by the broad, underfit, meadow-floored valley between the outlying granite hill and the rampart of Bishop tuff immediately west of the right-angle bend in Rock Creek at Toms Place. This large valley, from which thousands of cubic yards of rock have been stripped by erosion, is no longer the site of a major stream. It clearly seems to mark the abandoned course of Rock Creek on its way to Long Valley via the narrow defile which Crooked Creek now occupies.

Capture of Long Valley by the Owens River

The second phase of the local drainage history probably was the headward growth of the predecessor of Owens River from the Owens Valley and capture of Long Valley basin and its lake. Of the two sets of initial streams consequent upon the Volcanic Tableland, one flowing north to Long Valley, the other south to Owens Valley, the competence of the south-flowing streams, because of their steeper gradient, was incomparably greater. The south-flowing stream that was to become the Owens River also had a decided structural superiority over its competitors. The western half of its course parallels in part an east-trending synclinal flexure in the Bishop tuff—north of the Owens Gorge the tuff dips southward and away from Round Mountain, south of the Gorge the dip is north and away from the Sierra Nevada. This location gave the stream not only the major area of the surface drainage, originally consequent on the tuff, but as the canyon was deepened, it intercepted the large quantity of ground water moving through the permeable tuff, which south of the Owens Gorge originates in part as underflow from Rock Creek. Some of this water now escapes from springs in the south wall of Owens Gorge.

Where the Owens River crosses the Volcanic Tableland it appears to have commenced as a consequent stream on the initial surface of the faulted and arched Bishop tuff. When this stream, through superposition, unroofed the buried granite ridge near the present site of Power House No. 1, its headward growth was controlled to an increased extent by the fracture pattern of the bedrock. This is shown strikingly by the south-trending segment of Owens Gorge which closely follows the north-south strike of one of the principal faults crossing the Volcanic Tableland (map 1), in some contrast to the course of the original southeast-flowing consequent stream. Once the southeast-flowing stream by headward erosion cut through the drainage divide a short distance west of the south-flowing, fault-controlled reach, the dominant control was the regional dip of the Bishop tuff. When the drainage divide was breached, the headwaters of the west-flowing stream, tributary to Long Valley Lake, were captured, the drainage was reversed, and the present course followed by the Owens River through its deep gorge was established.

In view of the recency of deformation, an alternative possibility is that the Owens River is antecedent, and was established prior to the arching of the Volcanic Tableland. In view of the fact that the difference in altitude is only 280 feet between the highest recognizable shore line of Long Valley and the low point of the divide separating it from the Owens Valley, this alternative hypothesis is attractive. No incontrovertible evidence has been found to oppose it, but available facts seem to favor the greater likelihood of headward growth and capture. These data include (1) the close agreement between the regional slope and the course of the eastern, or consequent, sector of the Owens Gorge,

(2) the adjustment to structure in the central part of the gorge where the Owens River has been superposed on basalt and granitic rocks beneath the Bishop tuff, and (3) the great difference in altitude between Long and Owens valleys, which makes headward growth by a south-flowing stream the more plausible of the two possibilities. However, there is reason to believe that some uparching has been going on concurrently with downcutting of the Owens River in its gorge; a belief that is supported by the convex curve shown in figure 2 for the surface of the Volcanic Tableland. This leads to the conclusion that both factors may have operated together to produce the anomalous course of the Owens River across the Volcanic Tableland, and thus to have drained Long Valley Lake; of the two, headward growth appears to have been dominant over antecedency.

An essential part of the problem of the capture of Long Valley by the Owens River is the draining of the Pleistocene lake that once partly filled the basin. The actual manner by which this was accomplished is a moot point. Mayo (1934) states: "Across the volcanic tableland, Owens River has cut an imposing gorge. Headward erosion in this canyon, and consequent lowering of the outlet of Long Valley, has brought an end to the existence of the lake that once occupied the valley floor." This is the belief I share, but apparently it was opposed by the late F. E. Matthes (unpublished, undated notes on the margin of his copy of Mayo's paper): "Both the evidence of the two gorges which bifurcate close to the lake basin, and a consideration of the climatic condition (rainfall) required to enable a streamlet such as postulated by the author to erode headward, would seem to favor the explanation that the gorge of the Owens River was created by *overflow* rather than by headward erosion" (italics his).

In support of Mayo's belief is the fact that lake shore lines at the south end of Long Valley cannot be traced up to 7,280 feet, the altitude of the present drainage divide. The highest recognizable shore line which is nearest to the present outlet of Lake Crowley is at an altitude of about 7,000 feet, and no lake gravels are found on the Bishop tuff above this level. An additional point to be resolved by future work is whether or not lacustrine deposits at a higher altitude than this near the north end of the Long Valley trough are those of an earlier lake.

To summarize: Headward growth appears to be an entirely feasible mechanism for draining the lake for the following reasons: (1) although most of the arroyos incised in the Volcanic Tableland are dry weather ones, nonetheless, the larger streams, such as the Owens River, are perennial and doubtless derive a percentage of their discharge from underflow through the permeable Bishop tuff; (2) the difference in the local base level on the two sides of the tableland is very great (to the north the altitude of Long Valley is 6,900 feet, to the south the floor of the Owens Valley is at about 4,000 feet); (3) an argument in support of the presumed effectiveness of headward erosion by streams draining the southeastern flank of the Volcanic Tableland is the fact that a stream similar to the Owens River and now occupying Chidago Canyon, approximately 5 miles to the north, has cut a defile by headward growth and capture for a distance at least 5 miles farther into the range than the Owens River, yet Chidago Canyon has a much larger proportion of its length in granitic and metamorphic rocks; and (4) the possibly greater precipitation during the time of canyon cutting, which may have made for more effective stream erosion then than at present. Today, the summit of the Volcanic Tableland is scored by innumerable ravines no longer, or only rarely, occupied by running water, because meltwater from the snow is absorbed by the tuff about as rapidly as it is released.

ORIGIN OF ROCK CREEK GORGE

The third phase in the drainage evolution of the area concerns the somewhat parallel history of Rock Creek. As mentioned earlier, the original drainage of the Sierran part of the stream was northward to Long Valley at the same time that the south-flowing stream, now occupying Rock Creek, was extending its length northward from the Owens Valley. This latter stream finally succeeded in cutting through the barrier of granitic and metamorphic rocks underlying the Bishop tuff, which it unroofed at Sherwin Hill. Canyon-cutting in the Sherwin till was comparatively easy from here northward. As the drainage divide was breached, the south-flowing section of Rock Creek extended its course northward into Little Round Valley. The former channel, now marked by the arcuate meadow of Little Round Valley and the narrow defile of Crooked Creek, essentially is abandoned. It is now occupied by a markedly underfit stream supplied by one of the north-flowing distributaries of Rock Creek, and by seepage springs at the base of the fan.

CORRELATION

The precise time at which these captures and drainage reversals occurred remains unknown, but there is little doubt that it was late in the Pleistocene. The start of the gorge-cutting cycle was after the eruption of the Bishop tuff; emplacement of the Bishop tuff followed deposition of the Sherwin till. This means that if the Sherwin stage is synchronous with the Kansan glaciation, a number of important geologic events must be compressed into a short interval of Pleistocene time. Among these are: (1) the accumulation of at least 800 feet of pumice and rhyolite tuff, (2) faulting with a possible maximum offset of 500–700 feet, plus an indeterminate amount of warping, and (3) the cutting of two gorges, one 900 feet and the other 700 feet deep in rocks as resistant as granite, hornfels, basalt, and tuff.

In the Owens Gorge there is no direct evidence as to the time of canyon-cutting, other than the obvious fact that it was after the high stand of Long Valley Lake, which may have been coincident with the Tahoe glacial stage (Mayo, 1934). The mutual age relationship of the two gorges, Rock Creek and Owens, is not immediately apparent, although the bulk of evidence suggests that the Owens Gorge is older. In the first place, Owens Gorge is larger and deeper; secondly, it is the only south-flowing stream that succeeded in cutting completely across the Volcanic Tableland to capture the entire drainage of Long Valley; and thirdly, the upper part of Rock Creek was originally tributary to the Owens River by way of Little Round Valley.

The evidence of the Tahoe morainal and fluvioglacial deposits indicates that by the time of this glacial stage the lower part of Rock Creek had extended its course northward at least as far as Whisky Canyon, and possibly as far as the site of the present-day right-angle bend. If this is true, the reversal of drainage must have occurred at some time during the Tahoe stage.

Almost certainly there was a period during the Tahoe stage when meltwater from Rock Creek glacier drained both ways: (1) from Whisky Canyon arm southward via Rock Creek Gorge to Owens Valley, and (2) from Rock Creek Canyon northward via Little Round Valley to Long Valley. Evidence for the direction of flow of the latter stream is twofold: (1) the large underfit valley bounded by the outlying granite hill to the west, and by an escarpment 200 to 400 feet high of Bishop tuff to the east, and (2) by the deep narrows of Crooked Creek cut in the Bishop tuff. This narrow canyon serves as the connecting link between Little Round Valley and Long Valley. It is graded to the present level of Lake Crowley, not to the higher level of Pleistocene Long Valley Lake as it would have been had stream diversion occurred at the same time as the maximum expansion of the lake.

Excavation of Little Round Valley and the Crooked Creek defile seemingly demand a larger volume of water than is available for this task today. This may well have been provided by the meltwater of the north arm of Rock Creek glacier. There can also be little doubt that a greater flow of water than is characteristic of the diminutive stream of today was discharged through Little Round Valley during the Tioga stage when the large alluvial fan at the mouth of Rock Creek was growing actively. Then, as now, its distributaries must have flowed with about equal facility either into Long Valley, or south into Owens Valley by Rock Creek Gorge.

CONCLUSION

The evidence presented in this paper shows substantially that the following sequence of events may be responsible for the origin of Rock Creek and Owens River gorges immediately east of the central Sierra Nevada of California.

(1) Following the emplacement of the granitic intrusions that are the core of the Sierra Nevada in this region, erosion advanced to such a stage that most of the enclosing shell of metamorphic rocks was removed. Intrusive bodies were unroofed widely, and the whole area was probably reduced to intermediate relief.

(2) The oldest rock resting directly on this surface of denudation is basalt in the Owens Gorge with a maximum exposed thickness of flows and agglomerate of about 700 feet. These thin to a feather edge against a buried ridge of granite exposed in the walls of the Owens Gorge, which indicates that (*a*) the region was one of moderate relief before the outpouring of basalt, and (*b*) presumably some faulting preceded the basaltic eruptions.

(3) Outcrops show beyond doubt that the basalt is cut by faults, and that an episode of erosion intervened following this diastrophism, because the overlying rocks truncate some of these fractures and also bevel the tilted layers of basaltic flows and agglomerates.

(4) Glaciation was the next major event, and the evidence for it is the widely outcropping Sherwin till which has a thickness of at least 450 feet in Rock Creek Gorge. The till can be traced 3 miles east of the Sierran front until it is last seen in the walls of the Owens Gorge.

(5) Bishop tuff was erupted a short time after the Sherwin glacial stage, being emplaced as a succession of *nuées ardentes* with a maximum thickness of more than 750 feet in the Owens Gorge, where the base is unexposed.

(6) Faulting was active in the period immediately preceding the eruption of the Bishop tuff. Faulting continued following the consolidation of the tuff as is demonstrated by the faults visible in the walls of Owens and Rock Creek gorges and in Tunnel No. 1, where the largest fault cutting the tuff has a throw of possibly 500 feet.

(7) Erosion must have been active as well as effective shortly after the tuff was emplaced. Fault scarps on higher parts of the Volcanic Tableland are partially erased, and much of the Bishop tuff, as well as the exposed surface of the underlying Sherwin till, has been stripped away to produce a pedimented surface at the foot of the Sierra Nevada.

(8) Later phases of this erosional interval probably coincided with the advent of the Tahoe glacial stage. The only place in the area mapped where a Tahoe stage glacier was active was in Rock Creek Canyon where the glacier branched, with the larger arm moving northward into Rock Creek Canyon, and the smaller into the head of Whisky Canyon.

(9) Long Valley was occupied during the Tahoe glacial stage by a lake 13 miles long and as much as 200 feet deep. The highest shore line near Long Valley Dam is at an altitude of about 7,000 feet. The principal evidence for the existence of the lake within the area mapped is a wave-cut bench and its covering blanket of terrace gravels and algal reefs, best developed at several places along the eastern shore.

(10) The Volcanic Tableland of Bishop tuff was the southern margin of Long Valley Lake: higher shore lines are cut on the tuff and none of them have been found at the altitude of the divide, which is about 280 feet higher than the maximum level of the lake.

(11) Although glacial moraines and lake shore lines are nowhere in contact, the magnitude and number of events that are recorded since the lake was drained, including the cutting of Rock Creek and Owens River gorges, make contemporaneity with Tahoe rather than Tioga glaciation a more plausible time for the high stand of the lake.

(12) Capture of Long Valley as a result of headward erosion by the Owens River and downcutting of its gorge appears to be a more likely mechanism for draining Long Valley Lake than overflow.

(13) Rock Creek Gorge was excavated later than Owens Gorge and is a consequence of the headward growth of a stream paralleling the Owens River and the capture and southward diversion of an initially north-flowing stream draining into Long Valley.

(14) Ice of the Tioga glacial stage deepened Rock Creek Canyon and deposited much smaller lateral moraines than those of the preceding Tahoe stage. No terminal moraines survive inside the canyon, possibly because of their rapid removal by Rock Creek. The large alluvial fan at the mouth of Rock Creek Canyon seems to be of Tahoe and Tioga ages, and was built as the result of the many times greater volume of debris available to the meltwater streams of those times than to the Rock Creek of today.

ENGINEERING GEOLOGY OF TUNNEL NO. 1, OWENS GORGE PROJECT

The Owens Gorge Project of the Department of Water and Power of the City of Los Angeles is a hydroelectric development consisting of three power plants, all located within the Owens Gorge or its tributary canyons, together with five tunnels and the necessary connecting penstocks. Water for the system is supplied from Lake Crowley and regulated so that during times of peak demand releases are often greater than the entire normal discharge of the Owens River.

Tunnel No. 1 is wholly within the area mapped, and since the walls were open during the time I was engaged in field work, it provided me with an unparalleled opportunity to relate the surface to the subsurface geology. In addition to the cross section provided by the tunnel, I also had access to the logs and cores of five test holes drilled along the tunnel alignment for the city of Los Angeles, as well as the record of the shaft sunk for the surge chamber near the south portal. The Owens Tunnel Contractors also drilled a test hole on their own account at Station 193+10; I did not see the cores from this test, although the log was made available to me.

Geologically, the chief value of the tunnel and associated drill holes is the excellent data they provide on the thickness of the various layered rocks encountered and also their relative order of superposition. The tunnel section, for example, dispels all doubt that the Sherwin till was deposited before the Bishop tuff.

The total length of the new tunnel is about 30,224 feet from the adit connecting it with the old tunnel from Lake Crowley (Station 83+69) to the south portal (Station 385+93) above Power House No. 1. This pressure tunnel is now lined throughout its length with reinforced concrete or steel liners. It was excavated to a diameter of 12–13 feet and has an average finished diameter of about 10 feet, depending on the design of various segments of its length (Morris, 1954).

Driving started on September 1, 1949, at the north portal and on September 12, 1949, at the south portal. The two headings holed through on September 22, 1951, at a point approximately 12,348 feet downstream (Station 207+17) from the north portal. The bar scale below the tunnel cross section (fig. 1, in pocket), showing the progress by months, graphically indicates how much slower progress was toward the end of the project than the beginning. As might be anticipated, rates of advance correlate closely with conditions encountered. Progress through faults, water-saturated ground, and material with no strength whatever, such as glacial till, was less rapid than through the dry tuff.

Fortunately this tunnel was without some of the bizarre difficulties encountered in its predecessor, the Mono Craters Tunnel (Putnam, 1949) 18 miles north, in that it lacked nearly disastrous inflows of carbon dioxide and hot water. However, it did encounter a flow of water under pressure as well as heavy ground in the sections of the tunnel driven through water-saturated Sherwin till and Bishop tuff. These difficulties added greatly to the cost of the undertaking, and ultimately led to litigation between the Owens Tunnel Contractors and the Department of Water and Power of the City of Los Angeles.

The geologic map (map 1) and the cross section (fig. 1) show the location of holes drilled along the tunnel alignment. Holes 1-A, 1-B, 1-C, and 1-X were drilled in advance of construction. Holes OTC 193+10 and 210+72 were put down for additional information during the course of construction, the first by the contractor and the second by the city.[2]

In retrospect, the wide spacing of the test holes did not provide a realistic picture of the complex geology encountered underground along the tunnel alignment, and also did not reveal the fact that the water table stood 75 to 100 feet above the invert grade in the central section of the tunnel.

The various rock types encountered in the tunnel, as might be expected, responded in different ways to tunneling procedures. Engineers for the city of Los Angeles established a scale with values from 1 to 5 as a measure of rock competence, with 1 being a rock capable of maintaining an unsupported opening indefinitely and 5 being a rock having virtually no strength and requiring maximum support.

The first rock to be encountered in each heading was the Bishop tuff, and for the most part it proved ideal for tunneling operations. Its competence, when dry, was rated at 2 to 3, and only where it was broken by faults was it reduced to 4. Its great advantages for tunneling are made apparent by the bar diagram below the cross section (fig. 1) showing the supported and unsupported sections of the tunnel, which indicates that the first 5,300 feet driven downstream from the north portal required no significant support.

Most of the tuff encountered in the northern segment proved to be a sillar with numerous included pumice fragments and some lithic fragments, chiefly of shale hornfels. Pumice layers were rather common, especially in the basal layer, and this rock, where dry, made for exceptionally easy tunnel driving. It was in this section that the maximum advance of 2,142 feet in thirty-one working days was achieved (Morris, 1954). Of interest in the more consolidated tuff were the shear zones and small faults, some of which stood as open crevices for as much as 30 feet above the tunnel back (pl. 40, *b*).

Much of the tuff in the vicinity of the south portal approached an ignimbrite in texture, and the well-indurated groundmass contained numerous glassy, collapsed pumice fragments. It was also more conspicuously jointed, and in the vicinity of the surge chamber showed pronounced columnar jointing. The more blocky nature of the tuff here, perhaps in conjunction with its greater induration, made it necessary to provide support, where none had been required at the north end of the tunnel. The bar diagram shows that, with a few trivial exceptions, this section of the tunnel is continuously supported.

Difficulties developed with tunneling in the rhyolitic pumice and tuff as soon as water was encountered. The cross section (fig. 1) shows that water was a major problem in the tunnel between Station 139+00 and the vicinity of Station 264+00, a distance of 12,500 feet. The flow was perhaps greatest in the northern half, mostly in the sector between core holes 1-A and 210+72. Here, when the inflow was measured on October 24, 1951, the maximum appears to have been around 225 g.p.m.

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[2] The contractor's test hole, OTC 193+10, is not shown on the geologic map because I did not have an opportunity to visit it in the field and to locate it on the ground, as I did for all the holes drilled by the city, but the data uncovered by it are plotted on the cross section, since its stationing and log were made available to me.

The source of this large flow of water was investigated by engineers working on the project. The low precipitation—approximately 9.5 inches per year—and the absence of perennial streams on the Volcanic Tableland seemingly argue against any recharge by meteoric waters of a ground-water reservoir of the magnitude found here. A plausible suggestion advanced by some engineers was that much of this water was contributed by underflow from Rock Creek. At the point where it makes a right-angle bend near Toms Place, the stream is about 330 feet higher than the tunnel at Station 120+00—the point directly opposite the turn—and the stream profile does not intersect a plane passed through the elevation of the tunnel grade until it is opposite Station 223+00. The dip of the Bishop tuff and of the underlying Sherwin till is northward from Rock Creek toward the tunnel and the Owens Gorge, and both of these rocks appear to be good aquifers. Further support to this interpretation comes from the fact that several fair-sized springs break out on the south wall of Owens Gorge very near the western contact of the Sherwin till with the granitic rocks in the canyon bottom, which is at a point about 2.5 miles northeast of Toms Place. The lack of comparable springs on the north wall of the gorge supports the argument that at least part of the ground water intercepted by both the tunnel and the Owens Gorge comes from the south as underflow from Rock Creek. The waters of Lake Crowley and Rock Creek were charged with salt in order to determine the source of this water. Lake Crowley was eliminated with respect to Rock Creek.

In areas where Bishop tuff is water-saturated, and thus without strength, the tunnel required continuous support from closely spaced steel rib sets. This was especially true of shear zones in the tuff, many of which were characterized by broad bands of water-soaked gouge. In circumstances such as these the competence rating of the Bishop tuff diminished to values of 4 and 5, and in such areas steel ribs were set on spacings as close as 2 feet and continuous blocking and lagging as well as excelsior packing had to be used.

Great difficulties were experienced in tunnel driving in the Bishop tuff during July, 1950, in the north portal heading in the neighborhood of Station 180+00, and on August 24 there was a run of saturated material from the face at Station 182+89. A large volume of tuff and water ran into the tunnel and backed up for a distance of 400 feet and with a depth of 10 feet at the face. The contractor found no effective method for proceeding on the original tunnel alignment, so he was permitted to abandon the heading and tunnel on an offset route around the failure. The offset is shown as the jog in the tunnel alignment on the geologic map (map 1) in the vicinity of Drill Hole 1-A.

The new offset tunnel was started at Station 175+70, and at a short distance around the curve on the new alignment at Station 184+53 the tunnel heading encountered a steeply dipping and sharply defined fault contact between the Bishop tuff and the Sherwin till. This could well be the shear zone encountered at the heading on the original alignment where the failure occurred.

The Sherwin till presented a variety of tunneling problems. It is essentially a lightly consolidated deposit of angular or subrounded boulders, cobbles, and gravel set in a matrix of silt and sand. A deposit such as this does not show the stratification encountered in a water-laid sediment. The size range of the fragments encountered in the till, coupled with the lack of strength of its matrix, were leading factors in making this rock difficult to handle when saturated. Lack of strength made it necessary to provide a large amount of support, and the extreme variability of fragment size made tunnel-driving operations more difficult. According to analyses made by Water Department engineers, the clay content only rarely exceeded 4–6 per cent, although very often material of less than a quarter of an inch in diameter made up 60 per cent of the deposit.

Relatively rapid advances were made where the till was dry; on two occasions distances of more than 1,500 feet per month were achieved in the south heading, in spite of the fact that continuous support was required for all sections of the tunnel in glacial till. This was a better record than was achieved in granite, a rock that might be regarded by many as more favorable for tunneling.

Quite different conditions were found for tunnel sections driven in water-saturated glacial till, such as the stretch between stations 184+53 and 246+00 which, with the exception of one 600-foot stretch of weathered granite, was wet morainal material throughout. The till was not only water-soaked, thus making for heavy ground, but faulted as well. Most of these faults were small, but some appeared to be major fractures; at least they were characterized by sheared boulders and by gouge zones several feet wide. It was most impressive to see these faults cutting through boulders and unconsolidated till, and for the most part they had sharp, well-defined contacts.

Steel supports spaced from 4 to 7 feet proved adequate for most of the tunnel. In a few instances spacing of from 2 to 3 feet was utilized, and in a short stretch double steel sets were used to support spiling. Much of the section was blocked or lagged continuously. Forepoling was required in some of the saturated till to advance the heading. Twisted and deformed steel sets and crushed lagging developed in several parts of this section of the tunnel.

The granitic rocks encountered in the tunnel were chiefly quartz monzonite and closely related variants. These rocks presented little more than the normal run of tunneling problems encountered in granite. The only thing about the rocks here that was possibly out of the ordinary was the extensive development of closely spaced joints and faults, some of large, others of small, displacement, but nearly all marked by well-developed shear zones. In almost all instances these required extensive blocking and lagging, and in the wet section of the tunnel these bands of gouge were the source of inflows of water.

A further problem presented by this rock comes from the fact that much of the tunnel line, where it penetrates granite, is in a weathered zone, probably only a short distance below the former erosion surface now buried under the Sherwin till and Bishop tuff. The weathered granite, especially where fractures in it are water-filled, proved to be a rock of very limited structural competence, and was rated as 4 and occasionally 5.

The geologic cross section along the tunnel line (fig. 1) shows that with only insignificant exceptions, the granite required support throughout much of the length that it was penetrated underground.

The basalt seemingly gave no more than the ordinary amount of difficulty. Perhaps its unique feature was the rapid change in tunneling properties that it exhibited. This was a direct result of the nature of the rock which here consisted of thin-bedded, strongly jointed flows intercalated with layers of pyroclastic material, such as ash, cinders, and bombs. In general, these pyroclastics behaved much like their unconsolidated counterparts in the Bishop tuff, just as the basalt flows had about the same competence as closely jointed granite.

SUMMARY

The Owens Gorge Tunnel was not unique as such enterprises go, but its completion was unquestionably of some difficulty. A number of these obstacles might have been anticipated had a more complete geological investigation been made in advance of construction. Further, many of the physical conditions encountered underground could have been inferred from a detailed study of the relationships of the rocks exposed in the walls of nearby Owens River Gorge.

Perhaps the greatest need was for more drill holes put down at a closer spacing. The holes were drilled initially at an average interval of about a mile, a gap too wide to provide an accurate prediction of the complex structure in the mid-section of the tunnel.

Geologically, the tunnel was of great value. It provided an insight into one of the structurally complex parts of the area, and established beyond reasonable doubt that the Bishop tuff overlies the Sherwin till. The tunnel also yielded much information as to the unweathered appearance of the rocks of the area, as well as many of their other characteristics and mutual contact relationships which were not visible in outcrop. It also provided an excellent reference line for constructing a cross section through a critical part of the area, since the invert grade was at a sufficiently shallow depth that surface observations could be projected to the tunnel level with confidence. The combination of these two sources of information, at the surface and underground, yielded sufficient data to make a reasonably reliable interpretation of the nature and amount of displacement along the many faults cutting the Volcanic Tableland.

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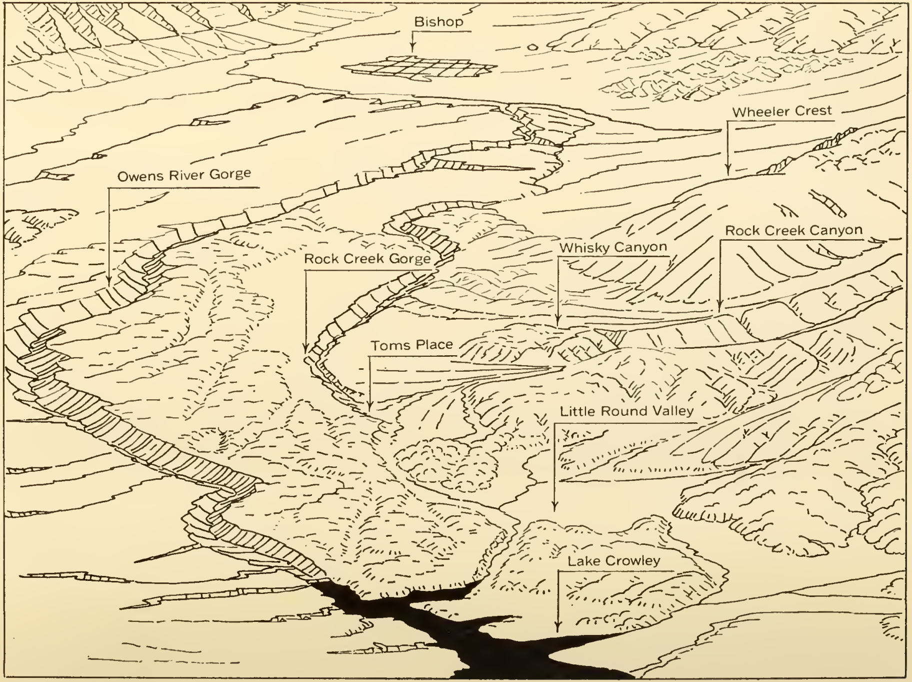
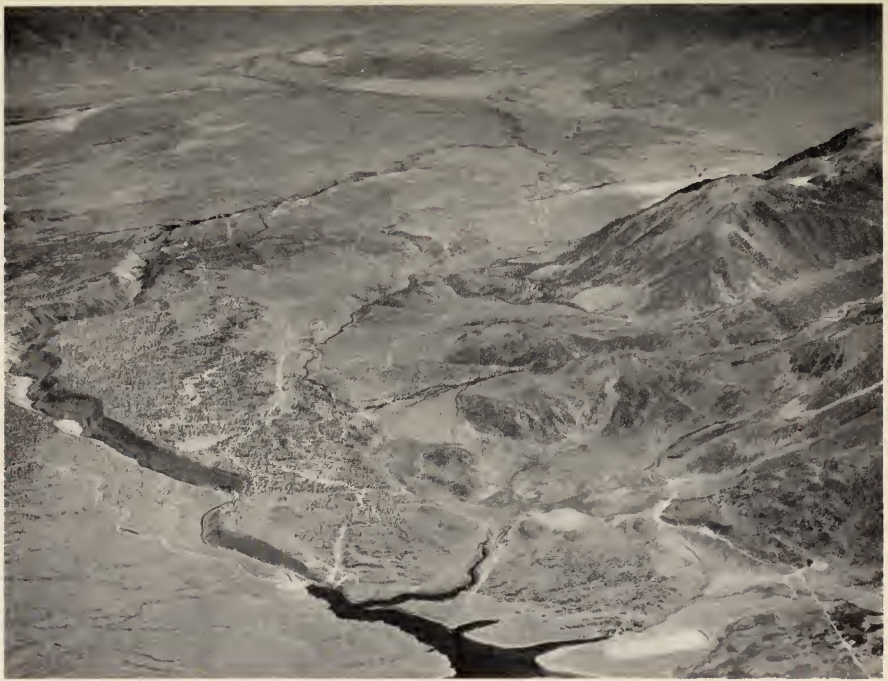
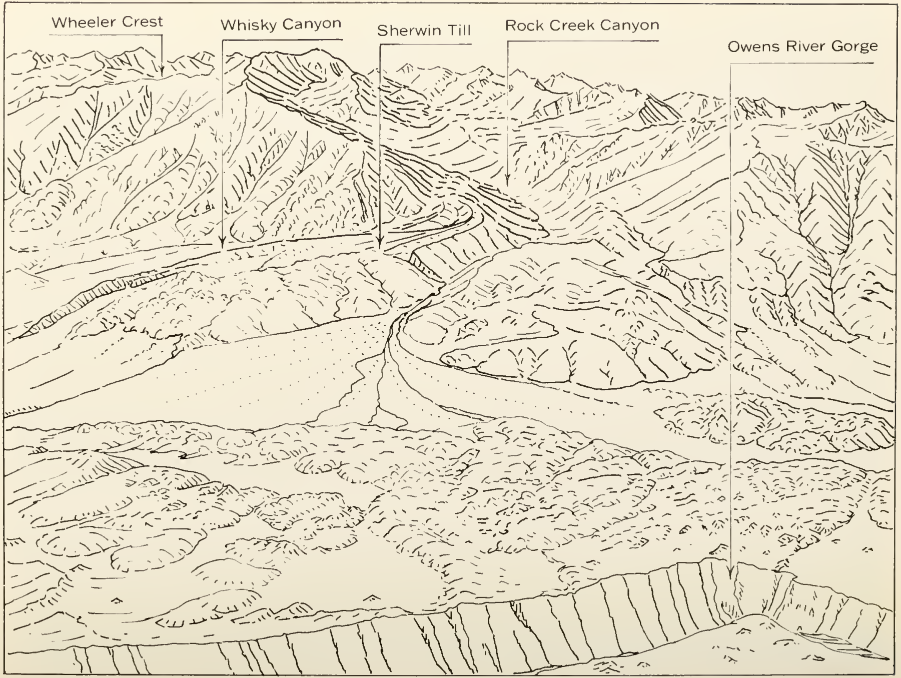
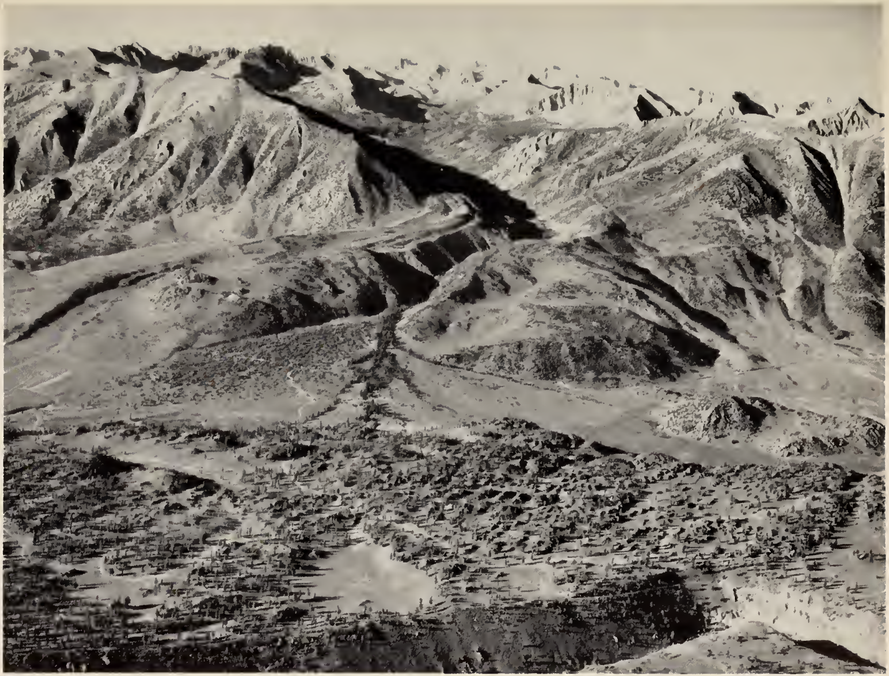

Bishop
Wheeler Crest
Owens River Gorge
Rock Creek Canyon
Whisky Canyon
Rock Creek Gorge
Toms Place
Little Round Valley
Lake Crowley



Oblique aerial view looking southward from Lake Crowley across the Volcanic Tableland toward the Owens Valley. The subparallel trenches of Rock Creek and Owens River gorges trend directly south, away from the observer. Toms Place and the Rock Creek alluvial fan are approximately in the center of the photograph. Photograph by Symons Flying Service.


Wheeler Crest
Whisky Canyon
Sherwin Till
Rock Creek Canyon
Owens River Gorge



First of three oblique aerial photographs looking westward toward the Sierra Nevada. Toms Place is near the center of the photograph at the mouth of the conspicuous trench of Rock Creek Canyon. The parallel ridges immediately south of the canyon are eroded lateral moraines of the Sherwin glacial stage in Whisky Canyon. Photograph by Symons Flying Service.

PLATE 33

Oblique aerial view looking westward toward the Sierra Nevada from approximately 5 miles east of Toms Place. Owens River Gorge is the conspicuous trench in the foreground; Rock Creek Gorge is the less obvious canyon in the middle ground. Light-colored rocks in the Owens Gorge are quartz monzonite in the core of the hill buried under a cover of darker basalt and rhyolitic tuff. Barren ground in the central part of the photograph is chiefly Sherwin till, wooded terrain in foreground is Bishop tuff. Photograph by Symons Flying Service.

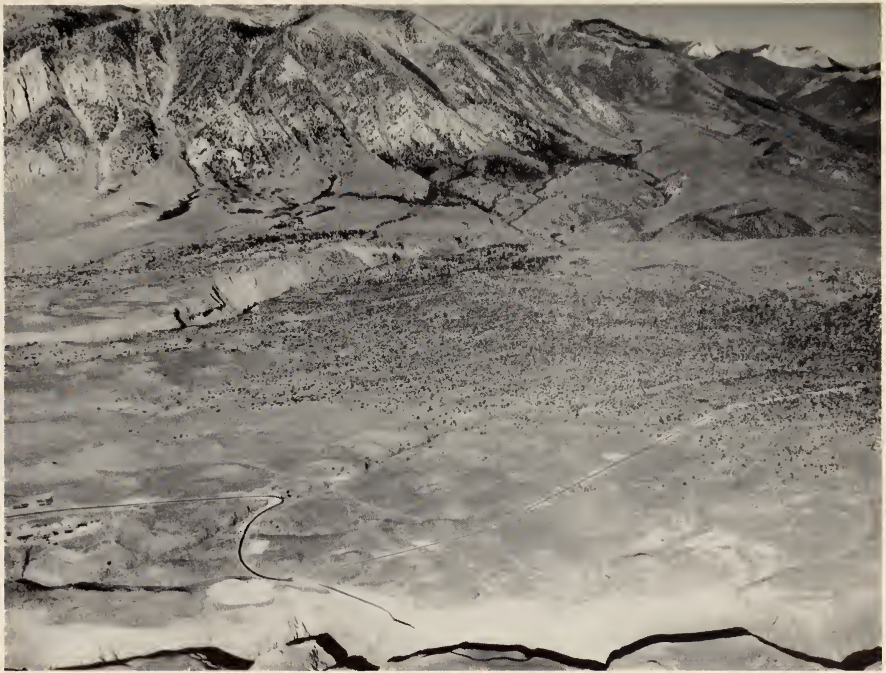


PLATE 34

Oblique aerial view looking westward toward the Sierra Nevada and across the Volcanic Tableland from a point approximately 7 miles southeast of Toms Place. Owens River Gorge is incised in the rhyolitic tuff in the immediate foreground and Rock Creek cuts through a section of Sherwin till, Sierran bedrock, and Bishop tuff in the middle ground. Photograph by Symons Flying Service.

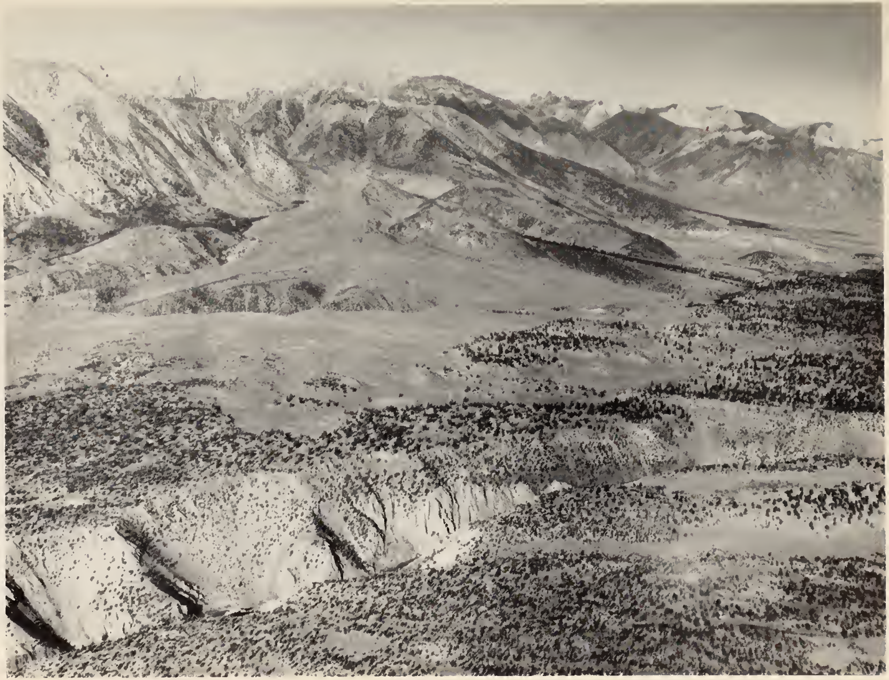
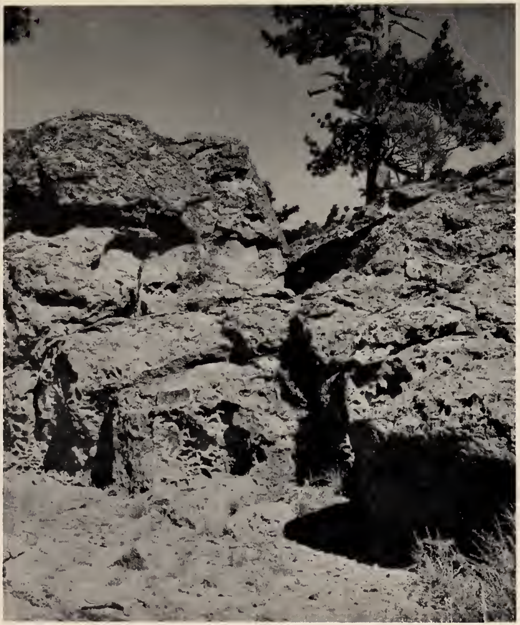


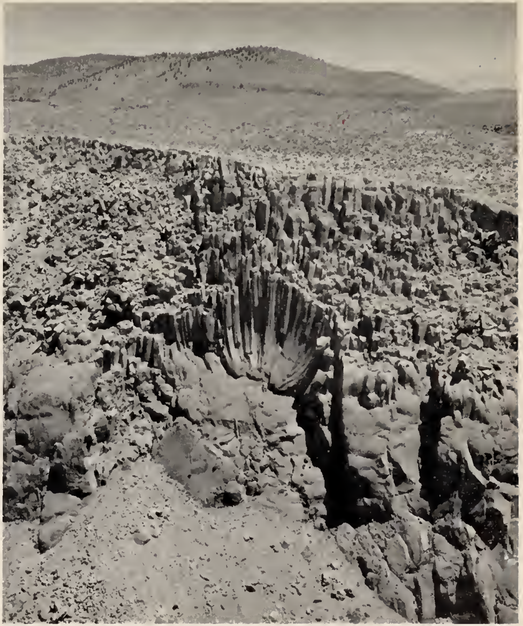
PLATE 35

a. Craggy surface and weathering pits that are characteristic of the Bishop tuff on the higher parts of the Volcanic Tableland. Photograph by T. C. Putnam.

b. Fanlike columnar joints in the Bishop tuff exposed in the walls of the Owens Gorge downstream from Power House No. 1. Photograph by T. C. Putnam.



a

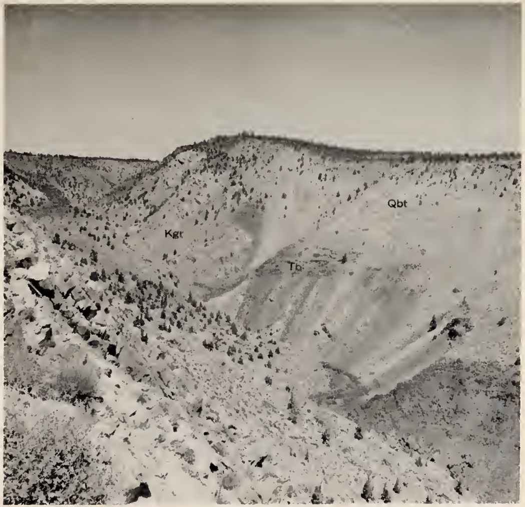


b

PLATE 36

a. View upstream at Power House No. 1 of the buried granite hill exposed in the walls of the Owens Gorge. Faults which are responsible for stepping down the overlying basalt cross the gorge in the middle of the photograph. Rock units are identified as follows: *Qbt*, Bishop tuff; *Tb*, basalt; *Kgr*, quartz monzonite. Photograph by T. C. Putnam.

b. View downstream in the Owens Gorge of the buried granitic hill immediately north of Power House No. 1. The sloping bedrock surface buried underneath the basalt is visible directly across the gorge, and the same volcanic rock has been dropped down by faults nearly to the level of the canyon floor on the downstream side of the granite hill. Rock units are as in *a*, above. Photograph by T. C. Putnam.



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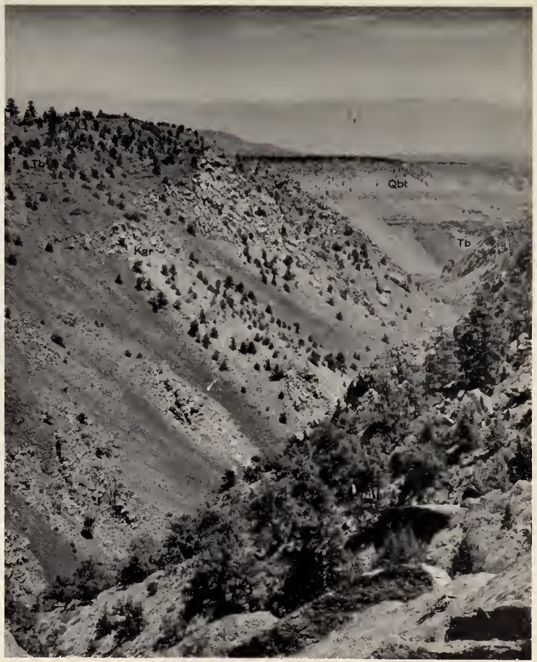
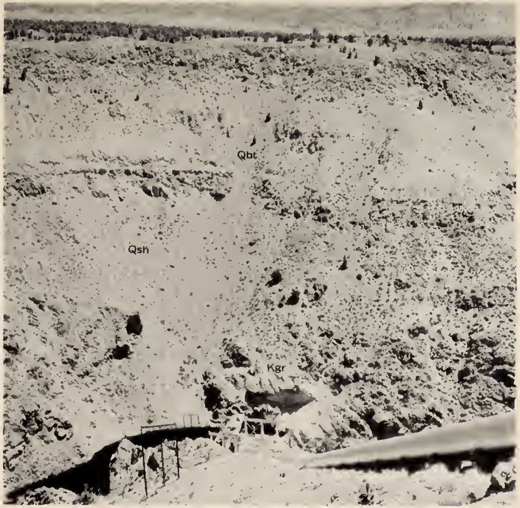


b

PLATE 37

a. Power House No. 1 showing a nearly complete section of the rocks exposed in the walls of the Owens Gorge, here approximately 700 feet deep. Rock units are: *Qbt*, Bishop tuff; *Qsh*, Sherwin till; *Kgr*, quartz monzonite. Photograph by T. C. Putnam.

b. View upstream near the central part of the Owens Gorge. Fault which has dropped basalt (*Tb*) down against the quartz monzonite (*Kgr*) is visible near the central part of the photograph. Photograph by T. C. Putnam.



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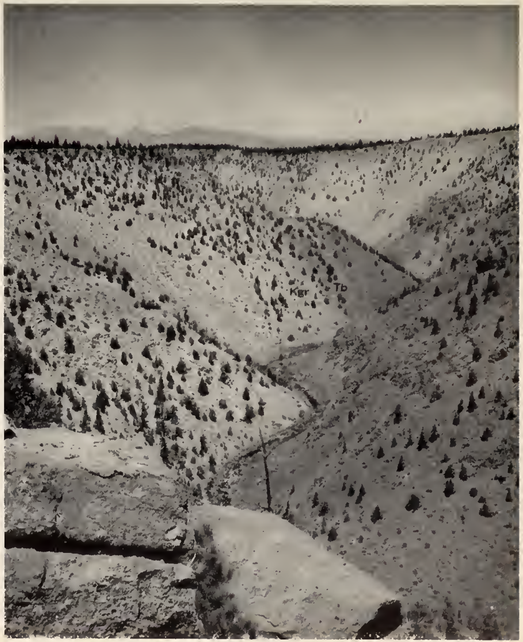


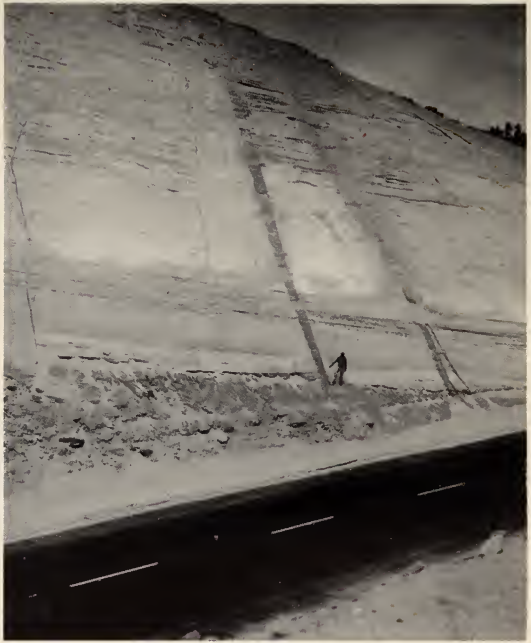
b

PLATE 38

a. View from immediately south of Toms Place looking north along the escarpment of the Sierra Nevada toward McGee Mountain. The conspicuous white road cut in the center of the photograph is the basal pumice of the Bishop tuff which here rests on Sherwin till. Photograph by T. C. Putnam.

b. Close-up of the pumice layer seen in a more distant view in *a*. The man is standing on the contact of the pumice with the underlying Sherwin till. The dark vertical bands are sandstone dikes. Photograph by T. C. Putnam.

a

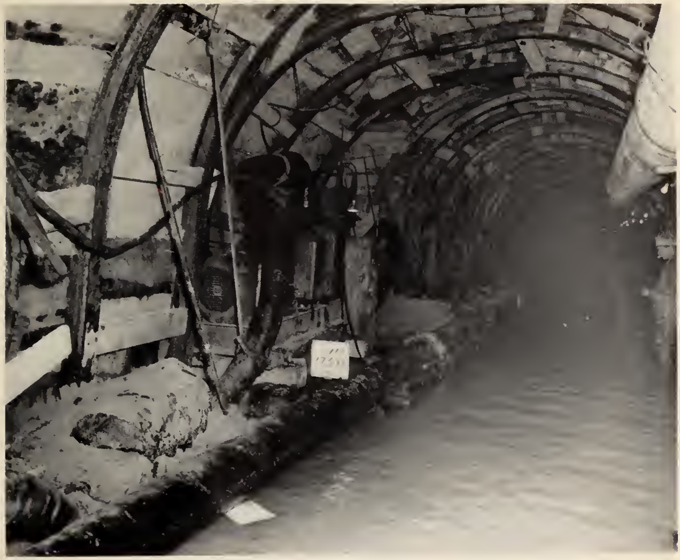


b

PLATE 39

a. Owens Gorge Tunnel at Station 173+15, immediately upstream from the collapsed heading. The tunnel here required continuous support and is in water-soaked Bishop tuff. Photograph by Los Angeles Department of Water and Power.

b. Continuously supported section of the tunnel in bouldery, water-saturated Sherwin till in the offset part of the tunnel in the general vicinity of Station 200+00. Railroad rails were used for spiling and blocking. Photograph by Los Angeles Department of Water and Power.



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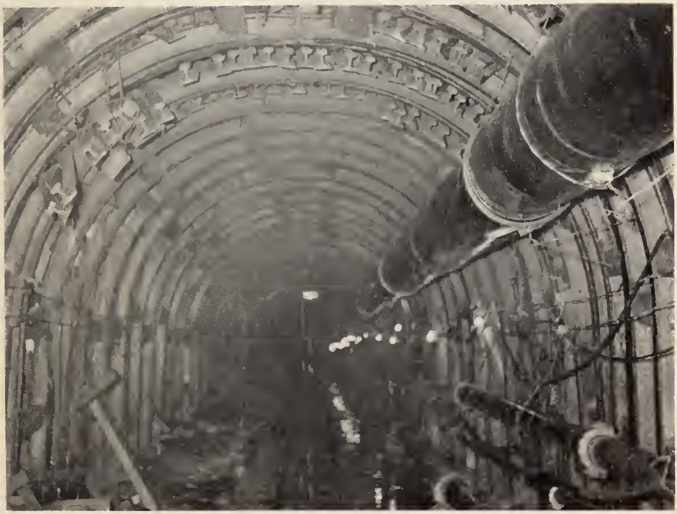
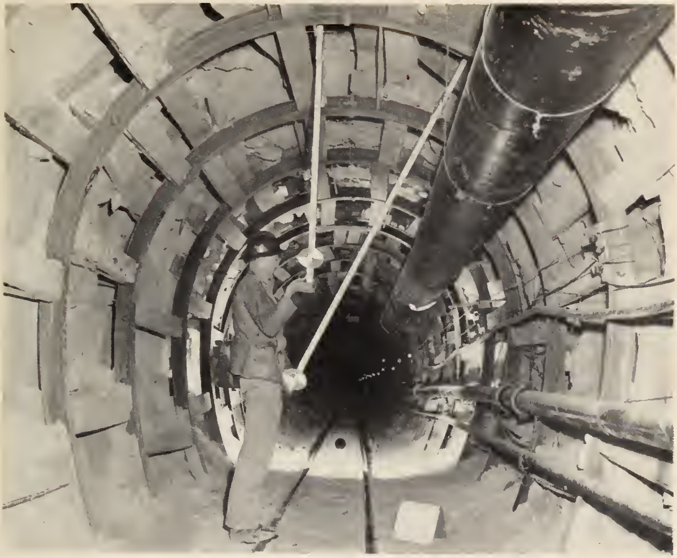


b

PLATE 40

a. Owens Gorge Tunnel in dry, relatively competent Bishop tuff at Station 370+95. Typical support required here is steel rib sets spaced 6 feet apart and a moderate amount of blocking. Photograph by Los Angeles Department of Water and Power.

b. Open fracture in dry, pumiceous Bishop tuff at Station 92+90. Some of these fractures were 3 feet across and extended upward for as much as 30 feet above the tunnel back. Photograph by Los Angeles Department of Water and Power.



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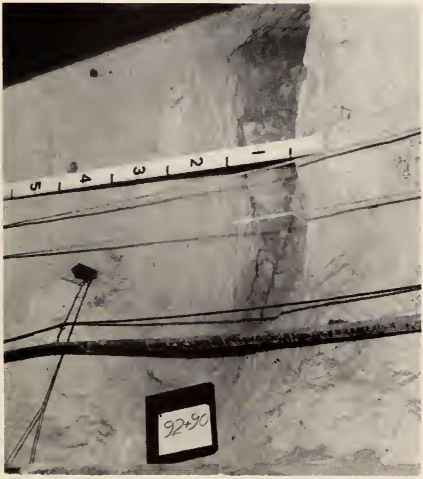

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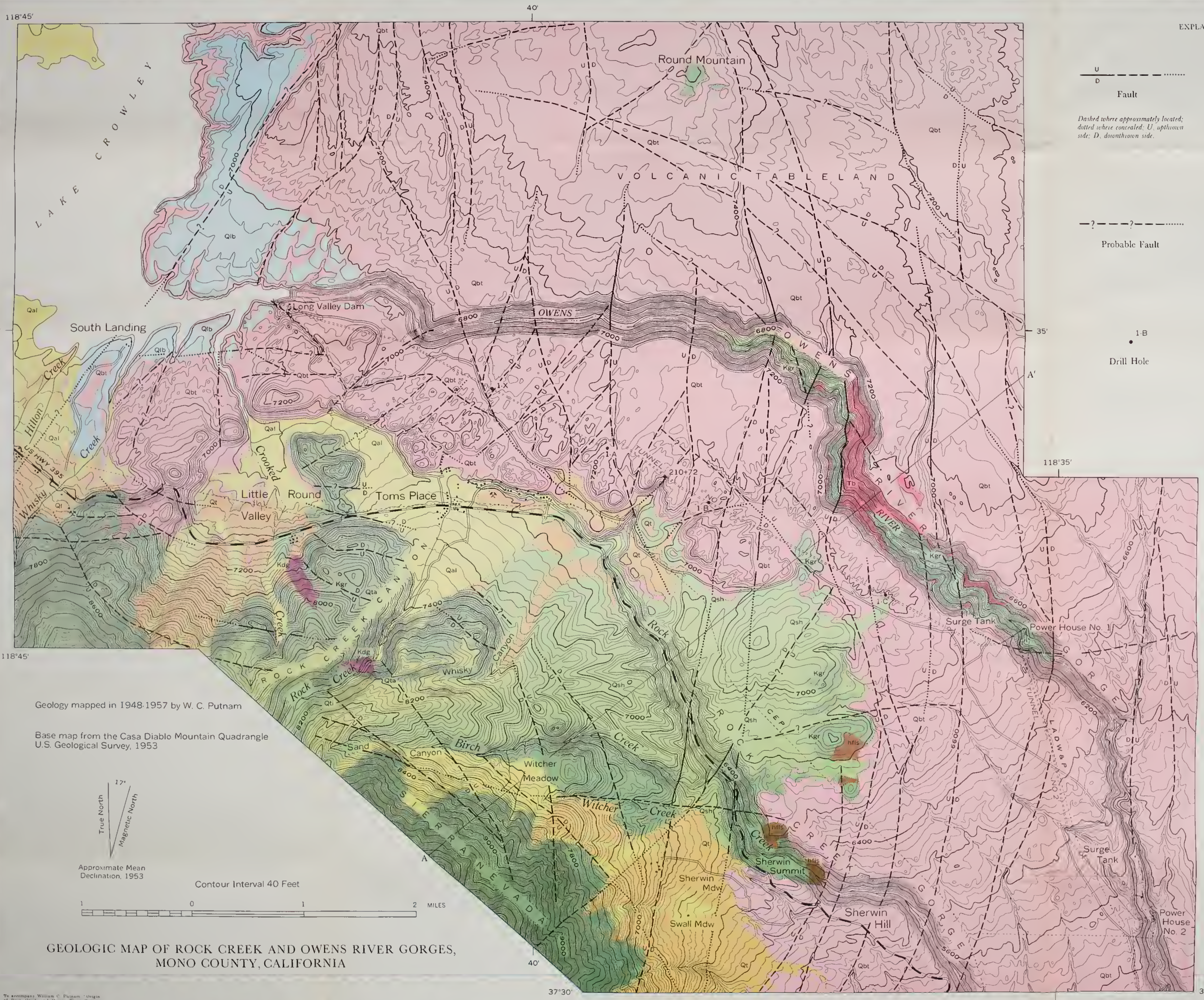


Geology mapped in 1948-1957 by W. C. Putnam

Base map from the Casa Diablo Mountain Quadrangle
U.S. Geological Survey, 1953

GEOLOGIC MAP OF ROCK CREEK AND OWENS RIVER GORGES, MONO COUNTY, CALIFORNIA

To accompany William C. Putnam "Origin of Rock Creek and Owens River Gorges, Mono County, California." Univ. Calif. Publ. Geol. Sci., Vol. 34, No. 5

EXPLANATION

U
—— — — — ……
D

Fault

Dashed where approximately located; dotted where concealed; U, upthrown side; D, downthrown side.

—?— — —?— — —……

Probable Fault

● 1·B

Drill Hole

QUATERNARY

Qal

Alluvium

Chiefly alluvium of talus cones and fans; lake beds adjacent to Lake Crowley; pumice in closed basins in the Bishop tuff.

Qt

Older Alluvium, Stream Terraces, Inactive Fans and Cones

Boulders, cobbles, and gravel of terraces and dissected alluvial fans.

Qlb

Lake Beds

Lake silt, sand, and gravel for the most part on wave-cut terraces east of Lake Crowley.

Qti

Tioga Till

Qta

Tahoe Till

Qbt

Bishop Tuff

Rhyolitic sillar, welded tuff, and interbedded unconsolidated pumiceous layers. White pumice bed characteristically at base, especially well-exposed east of Lake Crowley.

Qsh

Sherwin Till

TERTIARY (?)

Tb

Basalt

Thin flows of olivine basalt interbedded with agglomerate and cinders.

MAJOR ANGULAR UNCONFORMITY

CRETACEOUS

Kgr

Granitic Rocks

Chiefly medium- to coarse-grained, commonly porphyritic quartz monzonite. Minor local bodies of granodiorite.

Kdg

Quartz Diorite and Hornblende Gabbro

Medium- to coarse-grained rocks with varied texture. Gabbro in body south of Little Round Valley contains abundant large hornblende crystals.

PALEOZOIC AND PRECAMBRIAN

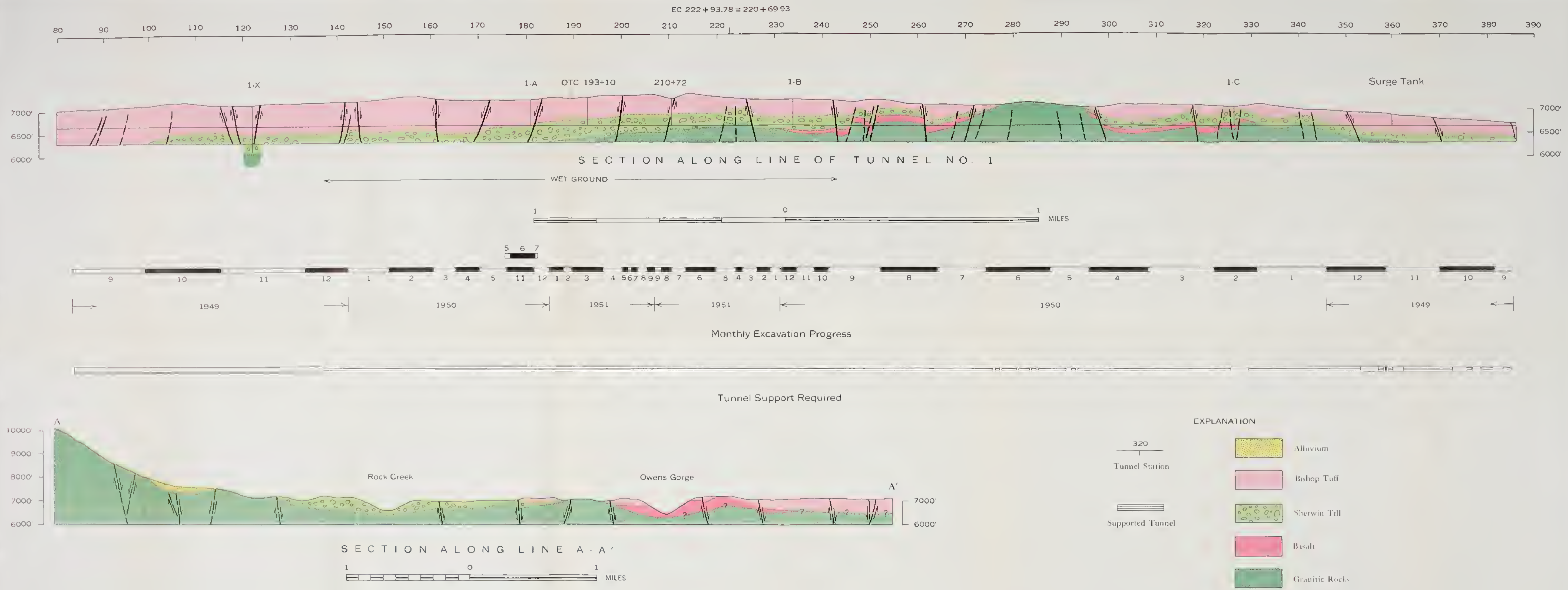
hfls

Contact-Metamorphic Rocks

[illegible] and calc-hornfels; minor amounts of marble.

Williams & Heintz Map Corporation, Washington 17, D.C.

Fig. 1. Geologic cross sections of Rock Creek and Owens River gorges, and of Tunnel No. 1, Owens Gorge Project, Mono County, California



GEOLOGIC CROSS-SECTIONS OF ROCK CREEK AND OWENS RIVER GORGES AND OF TUNNEL NO. 1, OWENS GORGE PROJECT, MONO COUNTY, CALIFORNIA

To accompany William C. Putnam, "Origin of Rock Creek and Owens River Gorges, Mono County, California." Univ. Calif. Publ. Geol. Sci., Vol. 34, No. 5

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